ervices Technical Information Ag

PLEASE RETURN THIS COPY TO:

ARMED SERVICES TECHNICAL INFORMATION AGENCY
DOCUMENT SERVICE CENTER
Knott Building, Dayton 2, Ohio

Because of our limited supply you are requested to return this copy as soon as it has served your purpose so that it may be made available to others for reference use. Your cooperation will be appreciated.

This Document
Reproduced From
Best Available Copy

25373

VERNMENT OR OTHER DRAWINGS, SPECIFICATIONS OR OTHER DAT.
PURPOSE OTHER THAN IN CONNECTION WITH A DEFINITELY RELA
UREMENT OPERATION, THE U. S. GOVERNMENT THEREBY INCURS
NOR ANY OBLIGATION WHATSOEVER; AND THE FACT THAT THE
AVE FORMULATED, FURNISHED, OR IN ANY WAY SUPPLIED THE
CIFICATIONS, OR OTHER DATA IS NOT TO BE REGARDED BY
ERWISE AS IN ANY MANNER LICENSING THE HOLDER OR ANY OTH
TION, OR CONVEYING ANY RIGHTS OR PERMISSION TO MANUFACT
TENTED INVENTION THAT MAY IN ANY WAY BE RELATED THERE

Reproduced by

DUMENT SERVICE CENTER

NOTT BUILDING, DAYTON, 2, OHIO



GENERAL ELECTRIC

Research Laboratory

FINAL REPORT
ONR PROJECT
Contract No. NONR 925(00)

December 1953

CLASS I

SCHENECTADY, NEW YORK

GENERAL ELECTRIC

Research Laboratory

Final Report

ONR PROJECT

RL-1007

Prepared by

Vincent J. Schaefer

Final Report Issued Under
Contract No. NONR-925(00)

Approved by

M. H. Hebb

Schenectady, New York
December 1953

FOR USE OF G-E EMPLOYEES ONLY

GENERAL ELECTRIC

Research Laboratory

SCHENECTADY, NEW YORK

TECHNICAL INFORMATION SERIES

Title Page

AUTHOR	SUBJECT CLASSIFICATION	NO.
Schaefer, Vincent J.	meteorology	RL-1007
		DATE: December 1953

TITLE

Final Report ONR Project 53-512

ABSTRACT

G.E. CLASS / GOV. CLASS.	REPRODUCIBLE COPY FILED AT	NO. PAGES
1	Research Publication Services Section	103

CONCLUSIONS

By cutting out this rectangle and folding on the center line, the above information can be filed into a standard card file.

INFORMATION PREPARED FOR Contract NONR-925(00)

TESTS MADE BY

COUNTERSIGNED DIV.

DIVISIONS LOCATION

VN-610-IM-RL (2-50)

TABLE OF CONTENTS

		Page
	Introduction	i
1.	A Correlation Between Atmospheric Electrical Activity and the Jet Stream Raymond E. Falconer	1
2.	The Concentration of Ice Nuclei in Air Passing the Summit of Mt. Washington Vincent J. Schaefer	31
3.	Ice Crystals Formed Spontaneously by the Rapid Expansion of Moist Air Vincent J. Schaefer	41
4.	The Measurement of High Concentrations of Ice Nuclei in a Small Parcel of Air Vincent J. Schaefer	51
5.	Silver and Lead Iodides as Ice-Crystal Nuclei Vincent J. Schaefer	59
6.	An Objective 30-Day Forecast Method for Precipitation and Temperature at Albany, New York, Using High-Pressure-Center Locations over North America Raymond E. Falconer and Kiah Maynard	69
7.	Observations of the Formative Stages of the Worcester, Massachusetts, Tornado Raymond E. Falconer and Vincent J. Schaefer . . .	89
8.	A Possible Relationship Between the Sign of the Potential Gradient and the Type of Particles in a Cloud Raymond E. Falconer	97

FINAL REPORT - ONR PROJECT

Prepared by
Vincent J. Schaefer

INTRODUCTION

In 1952, when it was decided to discontinue Project Cirrus since its major objectives had been achieved, some laboratory research studies remained in an uncompleted state while several promising leads required further exploration. Accordingly, a contract with the Office of Naval Research was proposed to cover those activities related to atmospheric physics. This was arranged and was effective for the year ending July 1, 1953. Papers describing the results of these studies have now been prepared and are assembled in this Final Report for Contract NONR-925(00), NR 082-101.

A brief summary of each of these studies follows.

1. A Correlation Between Atmospheric Electrical Activity and the Jet Stream, by R. E. Falconer. This study describes the strong correlation existing between the presence of a jet stream and the atmospheric electricity measured below it, using a radioactive gold point collector connected to a sensitive microammeter. A study was made of the fair-weather days from October 1952 through February 1953 when the radioactive collector current exceeded 0.05 microampere. On 80 per cent of these days, a jet stream was indicated by the WBAN isotach maps to be over the station at the 500-, 300-, or 200-millibar levels. It is suggested that a jet stream may carry a higher positive charge sufficient to increase the positive fair-weather current normally existing. This charge may be acquired by the jet stream as it passes over thunderstorms or other stormy areas previous to its arrival over a region of fair weather.

2. The Concentration of Ice Nuclei in Air Passing the Summit of Mt. Washington, by Vincent J. Schaefer. Since January 1948, the concentration of ice-crystal nuclei in air passing the summit of Mt. Washington has been sampled at three-hour intervals. More than 15,000 separate measurements have been made day and night throughout the seasons.

It is found that the concentration of ice nuclei at -18°C varies by a factor of more than a million. The highest concentrations observed are about 10 particles per cubic centimeter. It is not uncommon to note a

complete absence of ice nuclei at -20°C. When high-count values occur, they tend to persist for periods of six to sixty hours and seem to occur in air having a trajectory from the semi-arid regions of the West. In many cases, high concentrations occur when the major axis of a jet stream is over the mountain.

Previous to 1953, about half of the observations showed ice nuclei concentrations so low that supercooled clouds would be unaffected if formed in such air.

It is believed that most of the foreign particles which serve as ice-crystal nuclei are airborne aerosols which originally were of volcanic origin.

Low concentrations of ice nuclei had their highest incidence during the months of June, July, and August. In each succeeding year since 1948 this yearly effect was less pronounced, until in 1953 it failed to appear. It is suggested that this increase in ice-nuclei concentration may be reflecting the intensification and enlargement of the drought region in the southwestern states.

3. Ice Crystals Formed Spontaneously by the Rapid Expansion of Moist Air, by Vincent J. Schaefer. By compressing moist, nuclei-free air above 15 psi and then allowing it to expand rapidly into a supercooled cloud, concentrations of ice crystals equivalent to at least 1×10^{10} per cubic centimeter may be observed. These spontaneously formed crystals represent molecular aggregates of about 10,000 molecules, with each crystal having a diameter of about 0.008 micron. These crystals probably represent the survivors of a considerably higher concentration of primary particles, many of which contributed to the growth of those that are observed.

A new method for producing high concentrations of ice crystals continuously is mentioned. Further work using this method of ice-crystal formation would probably shed additional light on the size of primary ice crystals formed by the adiabatic expansion of nuclei-free air.

4. The Measurement of High Concentrations of Nuclei in a Small Parcel of Air, by Vincent J. Schaefer. A technique is described for the quantitative determination of high concentrations of ice crystals in a sample of air. The method may also be utilized for evaluating the relative behavior of various types of foreign-particle ice-crystal nuclei. It utilizes a constant and continuous flow of moisture fed to the floating

crystals that grow in turbulent air. Since the crystals are continuously growing and falling toward the floor of the chamber, the concentration as a function of time is a linear function when plotted on semilog paper. This relative concentration decreases linearly until it reaches a value of 1×10^8 crystals per cubic meter. Below this value, the crystals coexist with a supercooled cloud. Without competition from neighboring crystals, the remaining particles grow more rapidly as indicated by a break in the plotted data.

If the straight-line plot of the time-concentration values is extrapolated to zero time, it is possible to determine the initial concentration of crystals that reached the critical size required for survival.

The technique may be used for evaluating the effectiveness of foreign-particle nuclei, but care must be taken to exclude all traces of free iodine vapor.

5. Silver and Lead Iodides as Ice-Crystal Nuclei, by Vincent J. Schaefer. By using the continuous cloud chamber, a comparison is made between silver and lead iodide particles in their role as nuclei for ice-crystal formation. It is found that both of these iodides are effective as sublimation nuclei when forming ice crystals directly from the vapor to the solid phase. When compared as freezing nuclei, however, the silver iodide is far superior to lead iodide. Silver iodide causes water droplets to freeze between -4° and -5°C, while lead iodide has no appreciable effect on them until the temperature approaches -20°C. Silver iodide is probably more effective as a freezing nucleus because of its much lower solubility in water.

Because of the potential importance to experimental meteorology of the iodides that may serve as ice-crystal nuclei, further comparisons should be made of the many variabilities that can be introduced during the formation of such particles.

6. An Objective 30-Day Forecast Method for Precipitation and Temperature at Albany, New York, Using High-Pressure-Center Locations over North America, by R. E. Falconer and K. Maynard. An objective method is described by which 30-day forecasts of precipitation and temperature have been made for a specific area in eastern New York. An average accuracy of 72 per cent for a five-month period is found. The forecast of rain or no rain shows up particularly well in the analysis. The period from May to October has been considered in the initial effort. The system was originally tried for a one- and two-day forecast, supplemented later by five-, six-, seven-, and fourteen-day periods. The 30-day forecast has been more consistently accurate than any of the others.

An attempt was made with reasonable success to forecast precipitation amounts in four classes ranging from light to very heavy on the days for which rain was forecast.

The method, which is entirely objective, depends on the relative locations of high-pressure centers as published on the Daily Weather Map issued by the U. S. Weather Bureau. A simple transparent overlay bearing a grid system is used to obtain the basic data. This information is then referred to a master chart and the significant data are extracted. With the North American surface-pressure map currently available, a forecast for the 24-hour period 30 days hence may be prepared in less than five minutes. By this method it is feasible to prepare a running 30-day forecast.

Much more work remains to be done to explore the implications and physical reasons for the apparent success of this method.

7. Observations of the Formative Stages of the Worcester Tornado, by R. E. Falconer and Vincent J. Schaefer. The early formative stages of the severe storm that produced tornadoes in the New England states on June 9, 1953, are described. A sky camera located immediately west of Schenectady and covering the area between 45° and 165° recorded the developmental stages of the large cumulo-nimbus between noon and 3:30 p.m. Earlier in the morning, typical clouds that have been associated with jet streams were photographed. The WBAN isotach maps showed a 60- to 80-knot jet stream over Schenectady at the 500- and 200-mb level at morning and evening observations. A cyclonic motion was noted in the relatively small cloud system comprising the storm. Dry air aloft tended to cause cloud dissipation as successive cumulus towers overshot their equilibrium levels.

A peculiar and rarely experienced flow of atmospheric electricity was noted at the Research Laboratory by means of the radioactive collector. This started just five minutes before the tornado hit Petersham, Mass., and persisted as a strong current with a negative sig[illegible] 6:20 p.m., EST. This atmospheric electricity was accompanied by muc[illegible]adio noise of the precipitation-static type as observed on the long-wave radio.

8. A Possible Relationship Between the Sign of the Potential Gradient and the Type of Particles in a Cloud, by R. E. Falconer. Observations are presented relating the sign of the atmospheric electrical current received by a radioactive collector and the physical changes occurring within a cloud near the station. It is pointed out that experience in

observing storms and a study of the atmospheric electricity records gathered at the Research Laboratory indicates that a flow of positive current during stormy weather is indicative of ice-crystal formation, while a current flow of opposite sign indicates water-droplet formation either by condensation of water vapor as cloud droplets, melting of ice crystals, or both. The alternations in sign of the current flow during wet snow storms is interpreted as an indication of dynamic changes within the clouds in the vicinity of the station. Ice crystal formation, upward convection, and disappearance of the liquid phase would account for the positive sign, while the fall of snow crystals with the attendant melting, accumulation of water on the falling crystals, and decrease in concentration of snow would account for the flow of negative current.

The recent work of Reynolds at the New Mexico Institute of Mining and Technology shows results that agree with these field observations.

Part 1

A CORRELATION BETWEEN ATMOSPHERIC ELECTRICAL ACTIVITY AND THE JET STREAM

Raymond E. Falconer

For the past five years we have been making nearly continuous records of a number of meteorological variables at our weather station located at the General Electric Research Laboratory in Schenectady, New York. Most of the recording instruments were put into operation as part of the laboratory research studies conducted under Project Cirrus. Some of this type of study is now being carried on under a contract with the Office of Naval Research.

The instruments in use include some of the common ones found at most weather stations and, in addition, a number of new instruments that were developed during the course of the project.

Except for the occasional inoperation of equipment due to repairs, etc., we have continuous records of temperature, relative humidity, precipitation (heated tipping bucket), pressure, wind direction, wind velocity, solar radiation (Eppley pyrheliometer), reflected light from the northern sky, outgoing nighttime radiation (Gier and Dunkle flat plate radiometer), absolute moisture content of the atmosphere, variation in the electrical potential gradient (obtained by use of a radioactive point collector), concentration of condensation nuclei, and a count of the salt particles in the air. Many of these instruments have been recording since 1948, while others have been in operation for shorter periods of time. Most of the instruments use General Electric photoelectric recorders with chart speeds of two inches per hour.

Figure 1 shows the exposure site for most of the instruments, while Fig. 2 shows the installation of recorders in the weather office. Figure 3 shows simultaneous variations of several meteorological elements at times of different weather situations. The record charts for each 24-hour period are mounted, with times coinciding, in a manila folder, so that simultaneous activity on any or all of the instruments can be readily detected. A folder for each day since October 1948 is on file in our weather office.

Several months ago it became evident that such a large file of data should have some means for quickly determining the days on which particularly interesting weather phenomena occurred. This has been accomplished in part by adopting a color code using colored tabs

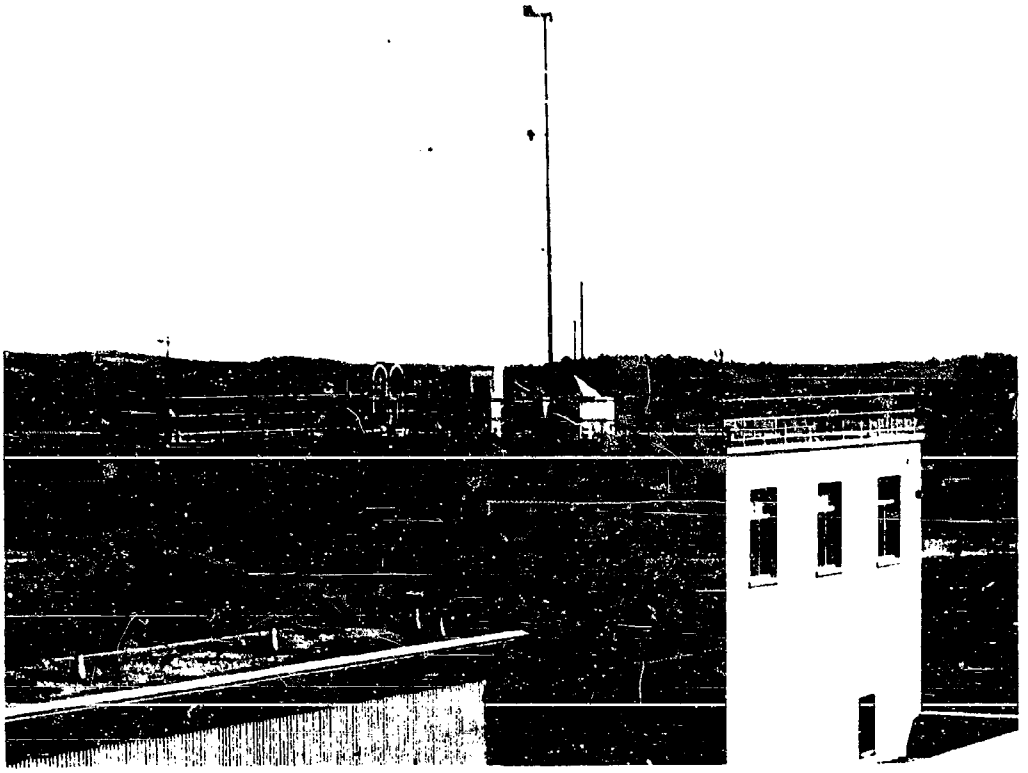


Fig. 1



Fig. 2

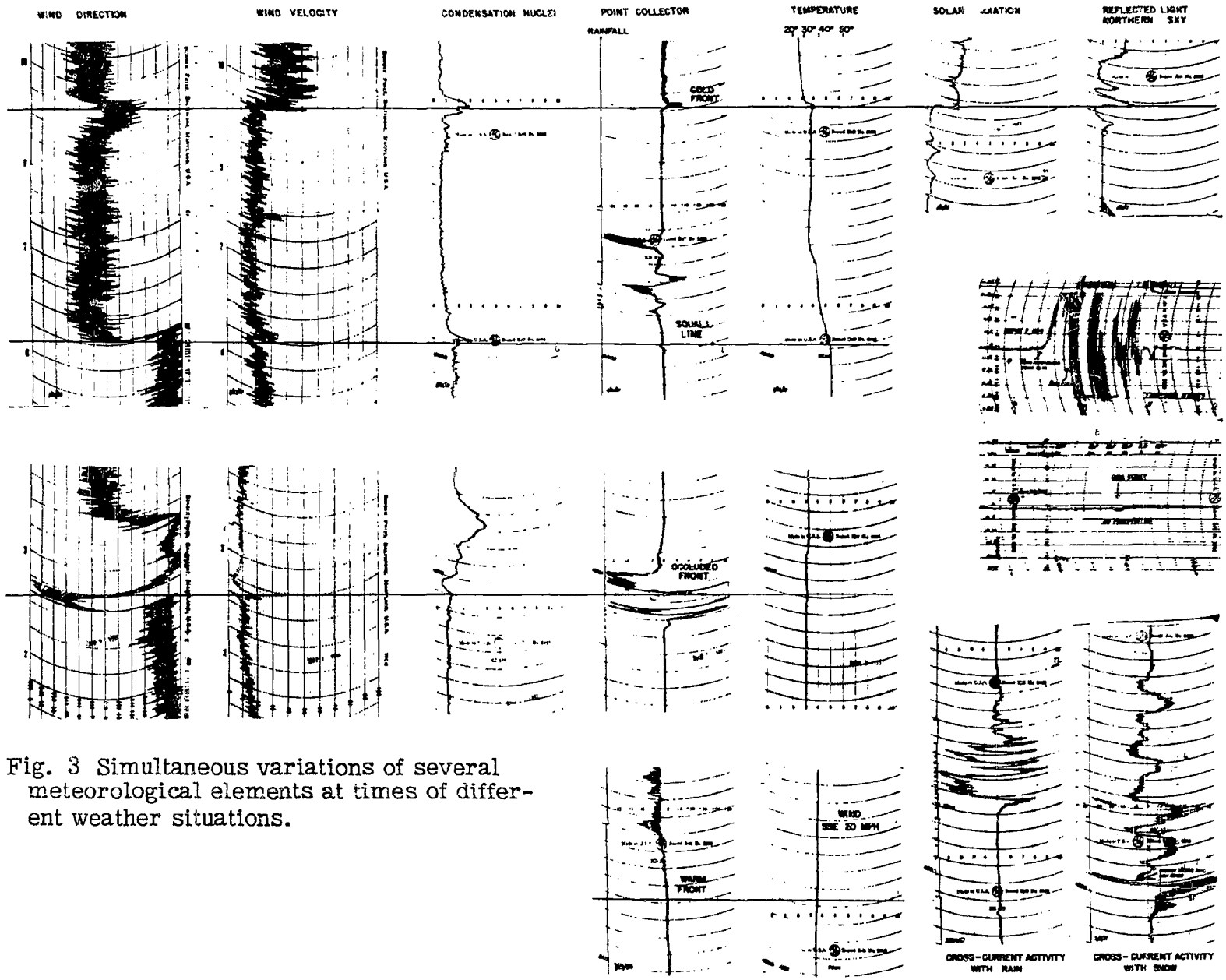


Fig. 3 Simultaneous variations of several meteorological elements at times of different weather situations.

attached to the exposed edge of each folder, as shown in Fig. 4. The position of the tab along the folder indicates the weather element of interest, while the color of the tab indicates the intensity, type, or other description. Clouds, fronts, precipitation, etc., are indicated in this way.

Last summer I assisted Vincent Schaefer in his study of cloud types related to the jet stream. I supplied him with jet stream locations as obtained from the WBAN 500- and 400-millibar facsimile charts received in our weather office each weekday by radio facsimile.

With the jet stream on my mind and while in the process of typing the daily weather folders, it occurred to me that it might be of interest to see what relation, if any, existed between certain increased positive currents in fair weather frequently noted on the radioactive point collector record and the presence of the jet stream over the area. A preliminary check indicated that higher positive current readings occurred in fair weather on days when the jet stream was near.

Before the results of more detailed comparisons are presented, it might be well to briefly describe the collector and some previous results. The mechanical arrangement of the point and insulator has been described previously in Project Cirrus Occasional Report No. 18,(1) but is shown here in Fig. 5. The brass point was sent to the United States Radium Corporation, where a length of radium-impregnated gold foil 2.5 millimeters wide by 0.005 inch thick was wrapped spirally along the 1/16-inch-diameter brass rod and made fast to it. The gold foil contains about 250 micrograms of radioactive material. The radium used in the foil is radium sulphate, having a half life of approximately 23 years. A point thus treated was obtained in 1948 and has been exposed daily since that time. Recently, 4-1/2 years later, two new points were ordered to be treated in the same way as the original one. After 4-1/2 years, little difference was noted in the characteristics of the old versus the new points. Figure 6 shows the variation in current in the radioactive collector circuit when various d-c voltages are applied to a metal cylinder 2.2 centimeters in diameter which is concentric with the collector.

Figure 7 shows an actual radioactive point and insulator assembly. This unit is mounted on a pipe 15 feet long, the point being connected to one side of a sensitive recording microammeter, located in the weather room, through a length of shielded R.G./8U cable. The other side of the recorder is grounded as is the shield around the cable.

(1) Falconer, R.E., "Some Correlations Between Variations in the Atmospheric Potential Gradient at Schenectady and Certain Meteorological Phenomena," Project Cirrus Occasional Report No. 18, G-E Research Lab. Rept. No. RL-287 (December 1949).

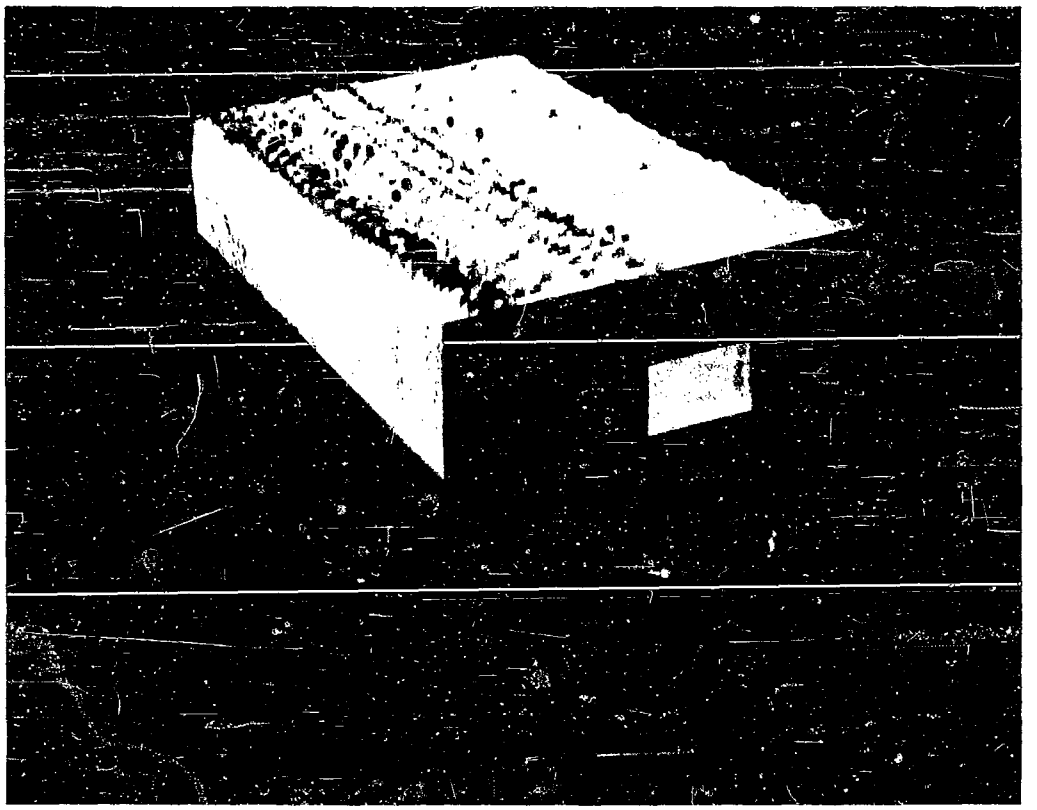


Fig. 4

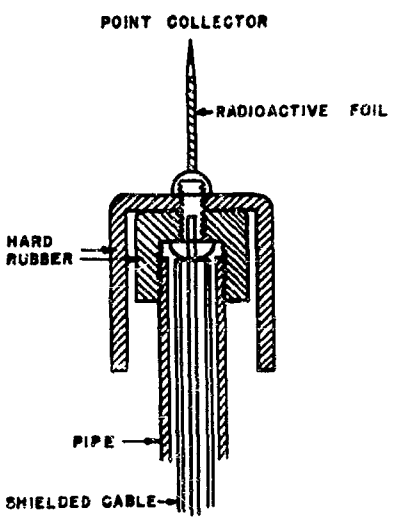


Fig. 5 Radioactive collector insulated mounting.

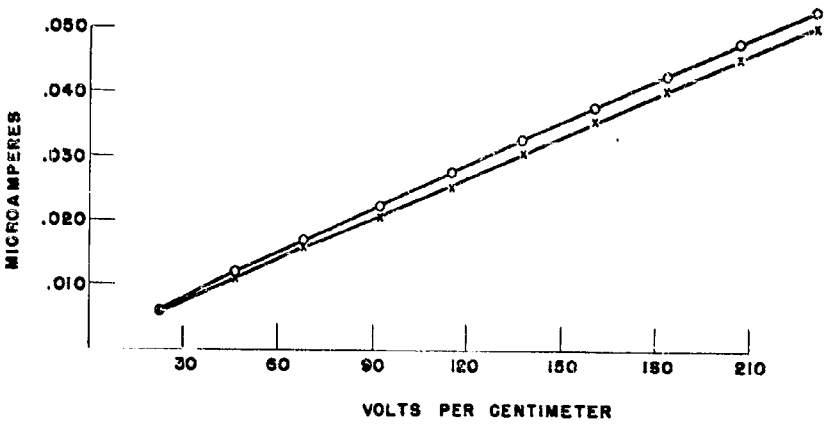

.050
.040
.030
.020
.010
MICROAMPERES
30
60
90
120
150
180
210
VOLTS PER CENTIMETER

Fig. 6

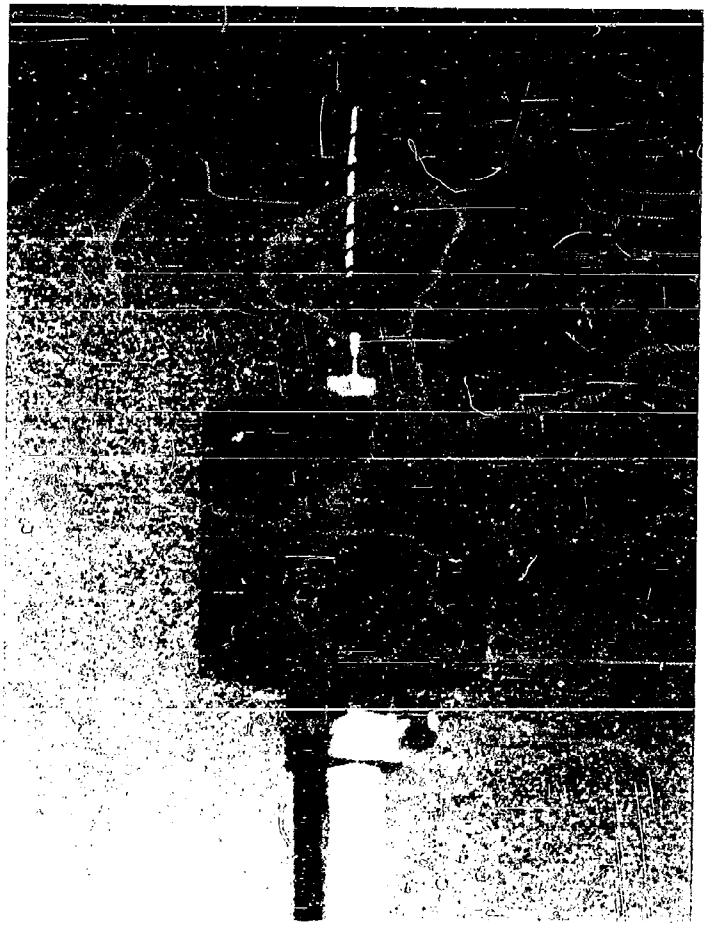


Fig. 7

From 1948 to the fall of 1951, the recorder in use had a sensitivity of 5.0 microamperes full scale. In the fall of 1951 an electrometer was added between the point and the recorder in order to increase the sensitivity of the system. Full scale on the recorder then equalled about 0.6 microampere. While it had been suspected that there was more structure to fair-weather currents than we had been recording, the greater sensitivity obtained with the electrometer verified this suspicion.

Through the winter of 1951-1952 it was noted that on some days, particularly clear, good-visibility days, the radioactive point record often showed higher positive current readings than on some other non-stormy days. Notes made on the daily records indicated some wonderment over this, and an attempt was made to correlate the higher positive readings with the appearance of cirrus clouds or ice crystals in the air.

It was thought at that time that possibly the Simpson-Scrase ice friction theory(2) of separation of charge might be responsible for these high positive current readings. We began to suspect that there were perhaps considerable numbers of ice crystals in the high atmosphere on days when the sky was apparently quite clear. This observation found some support when we later read a report on cirrus clouds by Fletcher and Sartor which appeared in Weatherwise for February 1952.(3) They report the following:

> "...1. Cirrus is more frequently encountered and more extensive than would be supposed from surface observations. With a surface report of one- or two-tenths cirrus coverage it is by no means uncommon for a pilot to report that he has been flying in or above an overcast cirrus layer. 2. Cirrus clouds are thicker than might be guessed from surface observations; thicknesses are frequently greater than 6000 feet and occasionally exceed 10,000 feet. ...4. In the upper troposphere there frequently exist haze layers which are not evident from the ground observations and which do not appear to be in the nature of ordinary cirrus. ..."

In addition to the ice friction theory, the possibility had been considered that, in the formation of high-level ice crystals or cirrus clouds, a separation of charge due to the change in state of water from vapor to ice might take place which would be of the right sign and magnitude to fit our observations.

---

(2) Chalmers, J.A., Atmospheric Electricity, Oxford University Press (1949), pp. 159-160.

(3) Fletcher, R.D., and Sartor, D., "Cirrus," Weatherwise, 5, 8 (1952).

At about the time it was discovered that there appeared to be some relation between the high fair-weather currents and the presence of the jet stream, a new electrometer was put into service in the radioactive collector circuit. The new electrometer provided full-scale sensitivity on the G-E photoelectric recorder of 0.55 microampere.

After a study of some of the records obtained by using this arrangement, it was determined that when the fair-weather current exceeded +0.05 microampere for a period of one or two hours or more, the jet stream was usually near. During cloudy conditions, it was determined that in most cases a positive current reading of +0.04 microampere or more would signify the presence of the jet stream. It should be mentioned that ordinarily when nonprecipitating clouds form or pass over the observation point in a deck, there is a noticeable decrease in the positive fair-weather current, although it does not usually go to zero or negative unless there is light precipitation. On the other hand, when the clouds dissipate or otherwise move well beyond the observation site, the current will then go more positive. These critical values may only be true for our location at Schenectady, and further detailed study might change them slightly.

In January of this year, preliminary data were analyzed which showed a good correlation between the days when the fair-weather current was believed to indicate the presence of the jet and the actual location of the jet within 150 to 200 miles, as indicated on our 1500Z 500-millibar maps received each weekday by radio facsimile. Weekend and holiday maps and the 0300Z maps were not available on this circuit, but even so there seemed to be a pretty definite indication that the jet stream, or at least high-level, high-velocity winds, might be detected by the increased positive fair-weather current.

Through the kindness of Harry Wexler of the Washington Office of the U.S. Weather Bureau and Ernest Christie of the New York office, the 200-, 300-, and 500-millibar maps from September 1952 through February 1953 were obtained to aid in making a more detailed comparison between electrical activity as observed at Schenectady and the presence of the jet stream over the area. For the purposes of this paper, only the period from October 1 on, after the new electrometer had been installed, has been used.

From each of the maps, the distance of the nearest jet-stream axis from Albany within a radius of 250 miles was determined. The indicated wind velocity over Albany was also noted. The daily charts of the radioactive point collector were then examined, although most

of them had already been typed with the color-tab system before the maps arrived. Days when there were few or no clouds, and with radioactive collector current readings of 0.05 microampere for an hour or more, were taken as indications that the jet stream was present. Some cloudy days when precipitation was not falling at the time were used if the positive current reading was 0.04 microampere or more.

Figure 8 shows a typical trace of the increase in positive current reading when the jet stream is near. In this case, the jet had not been plotted over our area for several days and was not expected to be near this day according to prognostic maps. However, shortly after 8 a.m. it was noted that the radioactive point recorder pen was climbing to current values usually associated with the presence of the jet. The current reading went down to a slight negative value after an hour or so as a very light sprinkle occurred, but this was followed by a definite increase in current reading to a value above the minimum of 0.05 microampere required for identification of the jet. The reading remained high for 3-1/2 hours. During this time there was a small break in an otherwise overcast sky, which was visible just to the west. There were some lenticular clouds visible near the break. It will be noted that during this period winds were fairly constant but diminishing in velocity toward the latter part of the period. We were pleased to note on the 1500Z 850-millibar map received by radio facsimile at 3:30 p.m. that afternoon that a jet was plotted exactly over the Albany area, as shown in Fig. 9.

Another good example of high positive currents associated with jet-stream activity is shown in Fig. 10. As can be seen, the current readings were high all through the night. Winds were generally light, averaging 10 mph, on the evening of January 15 and increasing to an average of 15 mph, all from the SE, during the early morning of January 16. A strong jet stream moved in from the west late on January 15, and its axis was plotted directly over Albany by the following morning with velocities of 140, 120, and 100 knots indicated over Albany at the 200-, 300-, and 500-millibar levels, respectively, as shown in Figs. 11 and 12.

On January 25 (see Fig. 13), we have one of the few cases where the point was high, indicating high-velocity winds aloft, but the jet axis was not plotted within 250 miles at any level. It was, however, plotted off the east coast and roughly parallel to it on the 1500Z 200-millibar chart as shown in Fig. 14. Winds were high, 140 knots, along the axis with the 80-knot isotach plotted right over Albany. Surface winds were rather strong on this day.

In the following tables are shown the results of comparisons between the days when the presence of the jet stream over the Albany-Schenectady area was indicated on the high-level charts and the probable presence of the jet as indicated by the increase in fair-weather current as determined from the radioactive collector record.

Table I shows the dates by months on which the jet-stream axis was plotted within 150 miles or less of the Albany-Schenectady area. It will be noted that a jet axis can be found within 150 miles of this area a large percentage of the time. During October 1952 it was within this radius at one or more of the three levels every day.

Similar tables were made for the times when the jet axis was within 100 miles and 50 miles of Schenectady, as shown in Table II. On the average it appears that, during winter months at least, the jet may be found within 50 miles of Albany 50 per cent of the time, within 100 miles 69 per cent of the time, and within 150 miles 83 per cent of the time, at some level between about 20,000 and 40,000 feet.

Table III shows the actual dates on which the radioactive collector current was believed to indicate the presence of high-velocity jet-stream winds aloft. There were 14 days during the 5-month period on which the jet stream was within 150 miles of Albany which were classified as stormy days and were not used in these comparisons. It should be kept in mind, however, that on these days atmospheric electrical activity is considerable and may be of both signs and large magnitude.

Table IV shows the dates on which the radioactive collector current was believed to indicate the presence of the jet stream when the jet was actually plotted within 150 miles of the Albany-Schenectady area.

In Table V, a summary of the results of the comparisons by months is shown, and Table VI gives a similar summary for the five-month period. From Table VI it will be noted that the jet-stream axis was plotted within 50 miles of the Albany-Schenectady area on 69 days and that the presence of the jet was detected correctly by the radioactive collector current reading on 61 of those days, or 89 per cent of the time. However, on five days during that period, it was felt the fair-weather current was not high enough to properly indicate the presence of the jet. Also, the point was thought to indicate the jet on 38 other days when the jet axis was not plotted within 50 miles.

(copy continued on page 24)

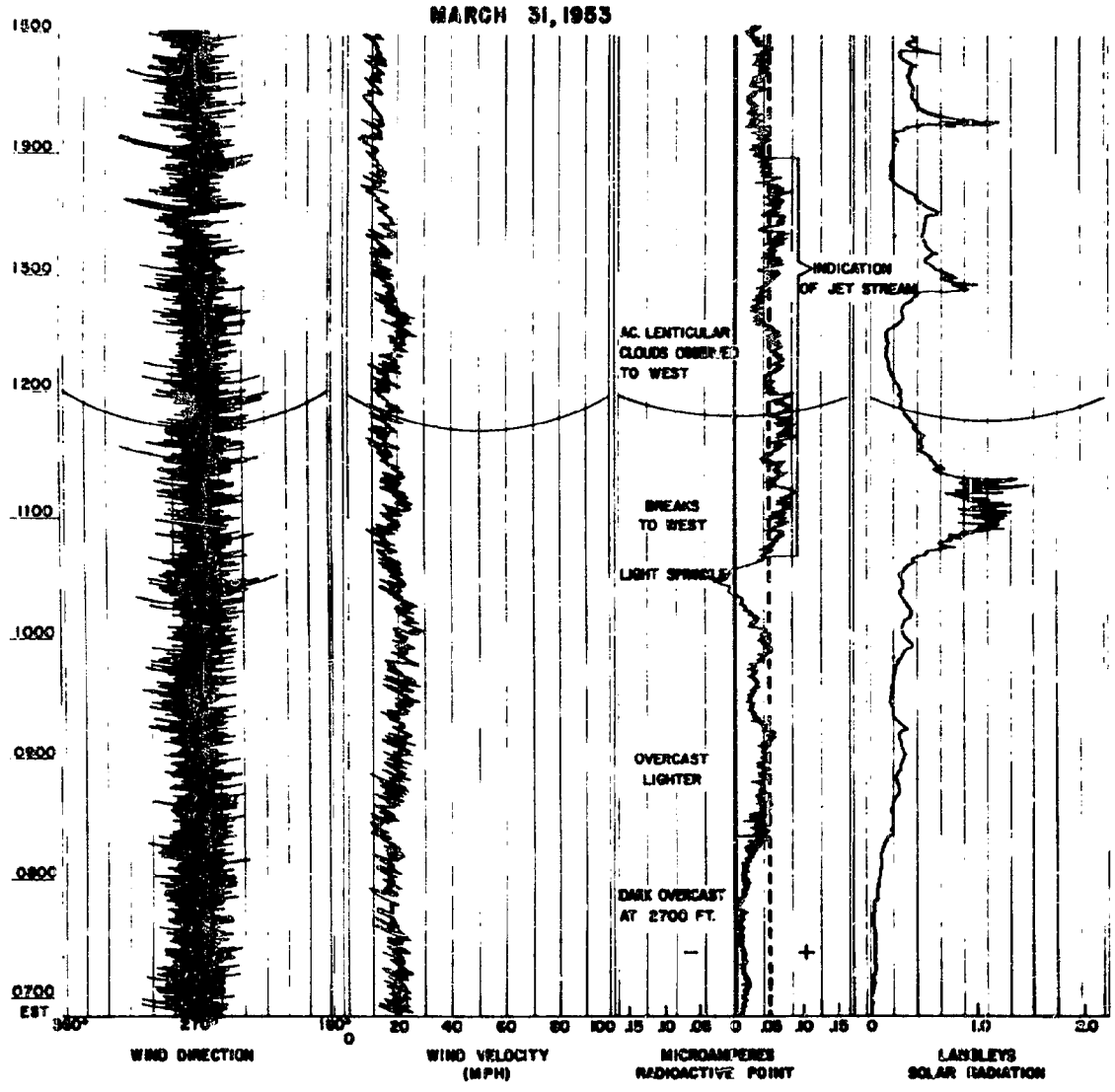

MARCH 31, 1953
1800
1900
1500
1200
1100
1000
0900
0800
0700
EST
AC. LENTICULAR CLOUDS OBSERVED TO WEST
BREAKS TO WEST
LIGHT SPRINKLE
OVERCAST LIGHTER
DARK OVERCAST AT 2700 FT.
INDICATION OF JET STREAM
360°
270°
180°
0
WIND DIRECTION
0 20 40 60 80 100
WIND VELOCITY (MPH)
.15 .10 .05 0 .05 .10 .15
MICROAMPERES RADIOACTIVE POINT
0 1.0 2.0
LANGLEYS SOLAR RADIATION

Fig. 8

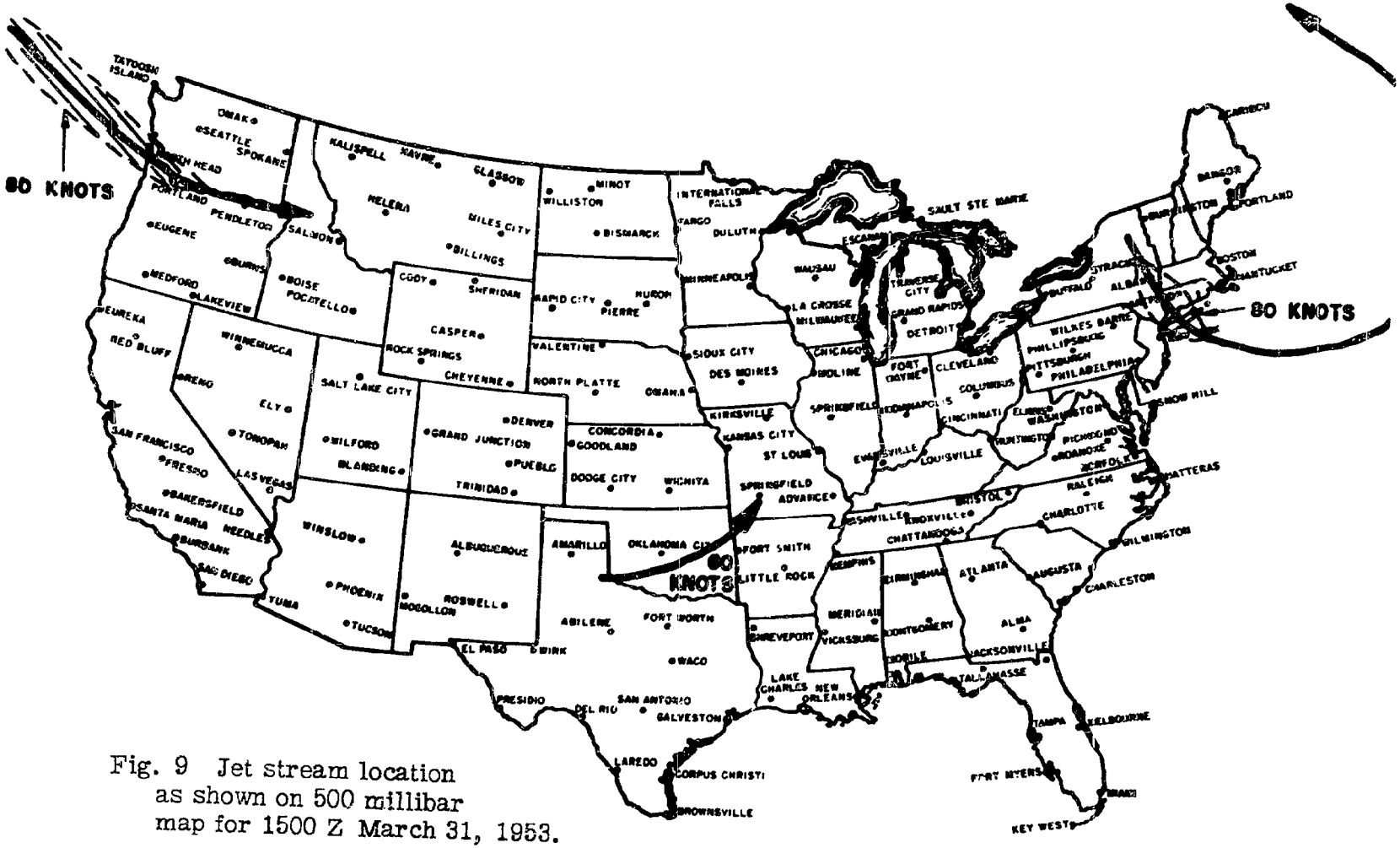


Fig. 9 Jet stream location as shown on 500 millibar map for 1500 Z March 31, 1953.

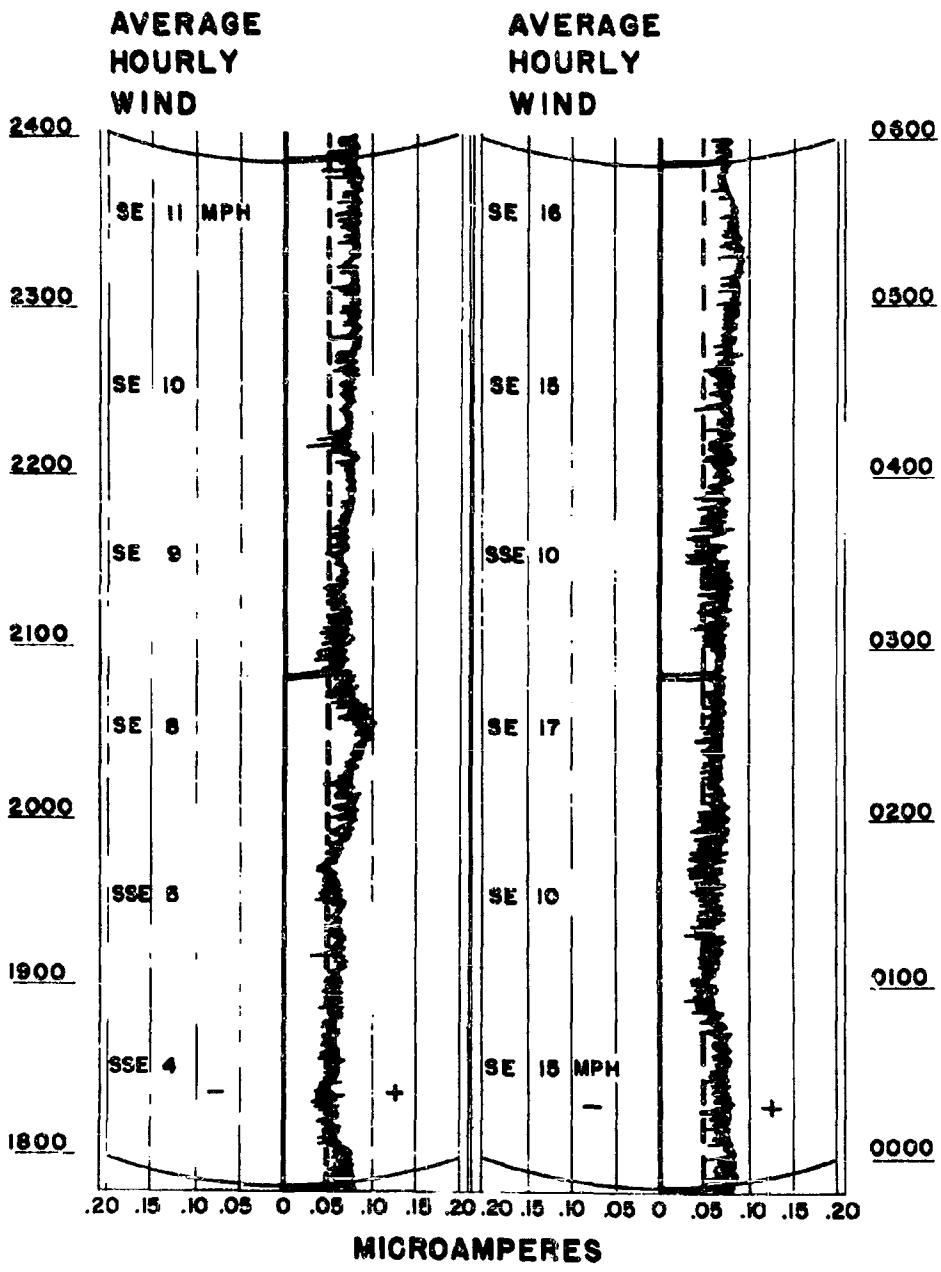


Fig. 10 Radioactive point record from 1800 January 15 to 0600 on January 16, 1953.

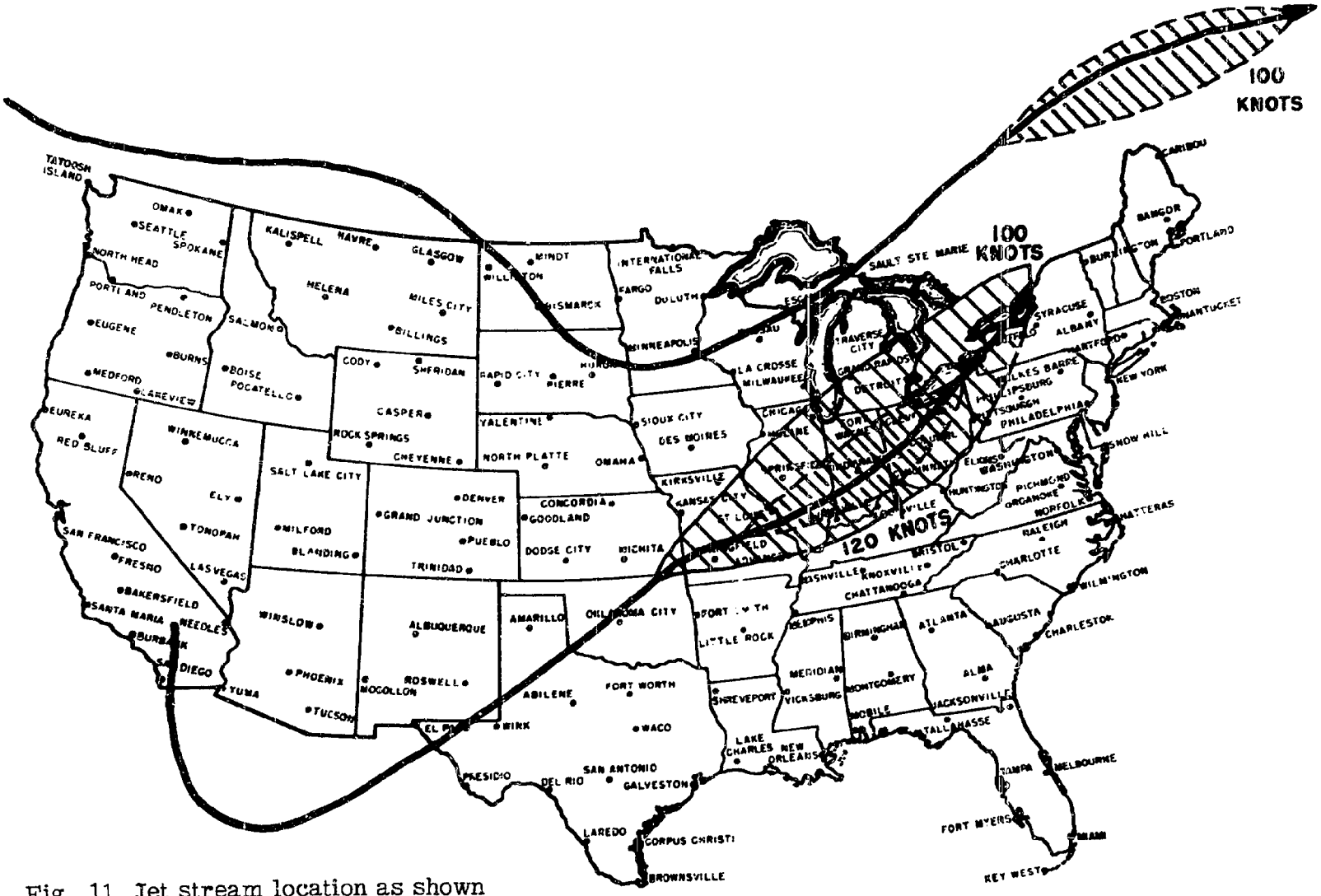


Fig. 11 Jet stream location as shown on 200 millibar map for 0300 Z January 16, 1953.

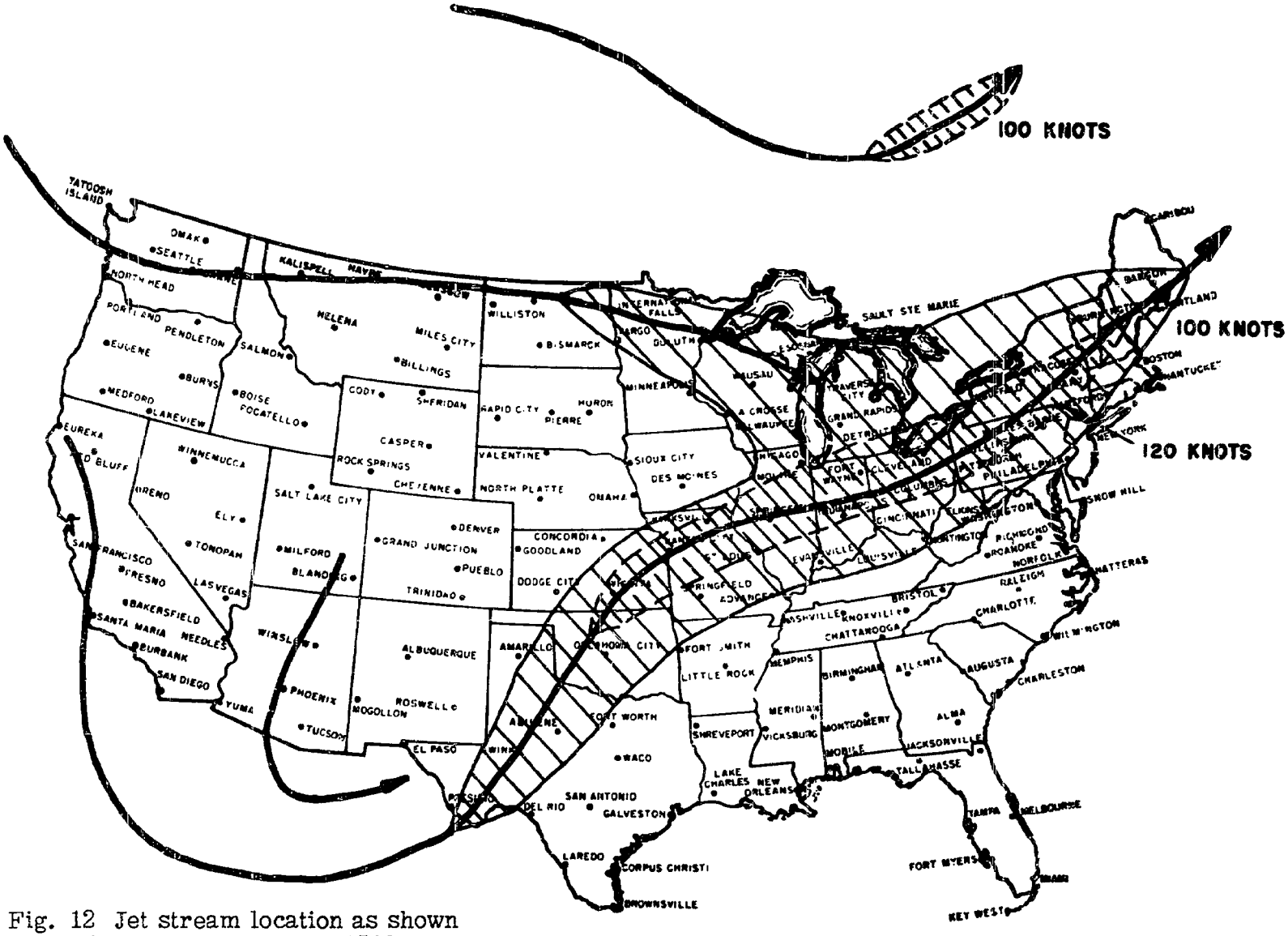


Fig. 12 Jet stream location as shown on 200 millibar map for 1500 Z January 16, 1953.

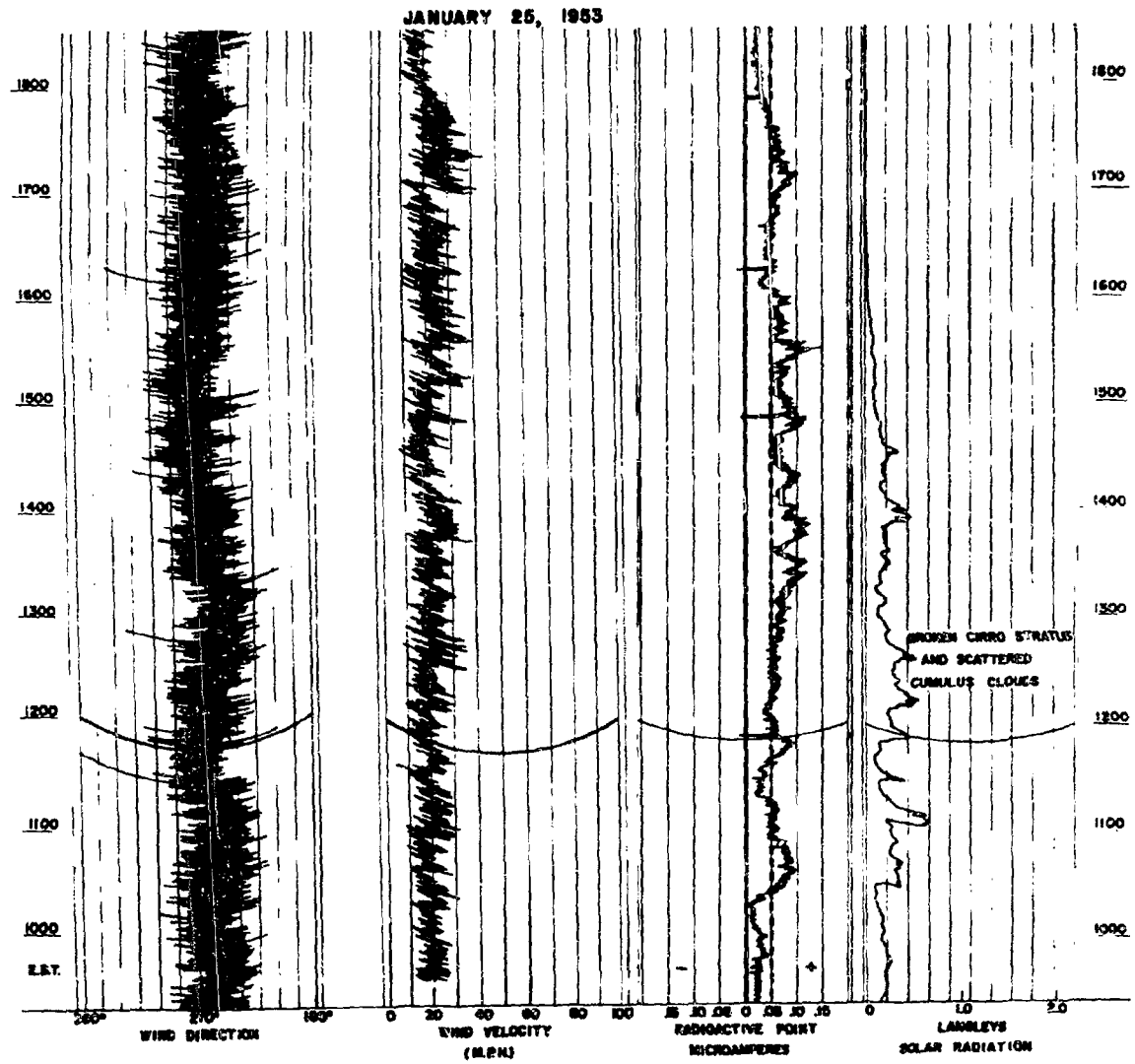

JANUARY 25, 1953
1800
1700
1600
1500
1400
1300
1200
1100
1000
E.S.T.
260°
270°
180°
WIND DIRECTION
0
20
40
60
80
100
WIND VELOCITY
(M.P.H.)
.15
.10
.05
0
.05
.10
.15
RADIOACTIVE POINT
MICROAMPERES
0
1.0
2.0
LANGLEYS
SOLAR RADIATION
BROKEN CIRRO STRATUS
AND SCATTERED
CUMULUS CLOUDS

Fig. 13

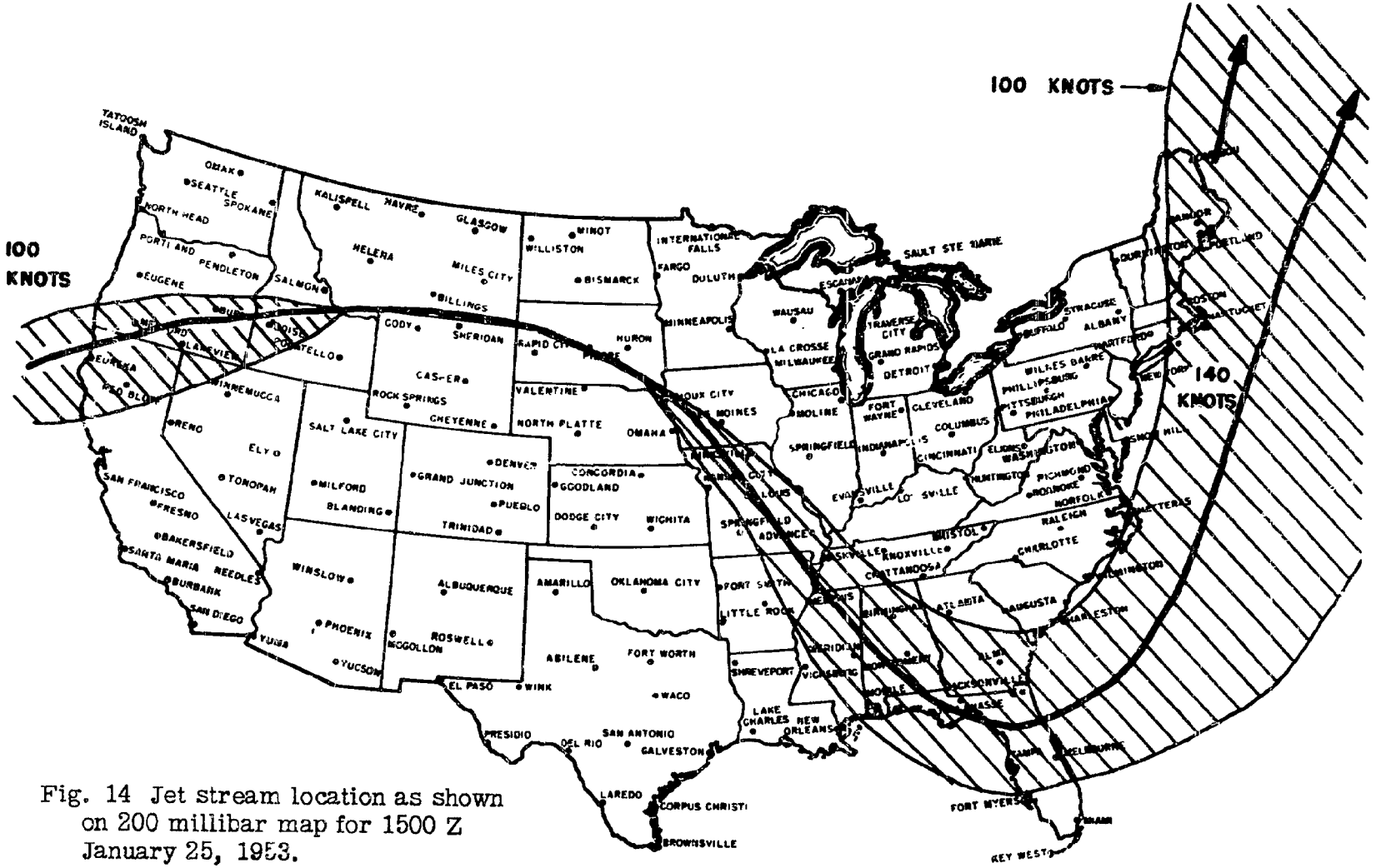


Fig. 14 Jet stream location as shown on 200 millibar map for 1500 Z January 25, 1953.

TABLE I

Dates on Which the Jet-stream Axis Was Plotted within 150 Miles or Less of Albany, N. Y., on the 200-, 300-, or 500-millibar Map

Sept. 1952	Oct. 1952	Nov. 1952	Dec. 1952	Jan. 1953	Feb. * 1953
1	1	3	1	1	1
2	2	4	3	2	2
3	3	5	4	3	3
4	4	8	5	6	4
5	5	9	6	7	5
7	6	10	7	8	6
8	7	11	9	9	7
9	8	12	10	10	8
10	9	13	11	13	9
11	10	14	15	14	10
12	11	16	16	15	11
13	12	17	17	16	12
15	13	18	18	17	13
16	14	19	19	18	14
17	15	20	20	19	15
18	16	21	21	21	16
19	17	22	23	22	19
20	18	23	24	23	21
21	19	24	25	24	22
22	20	26	26	26	23
23	21	27	27	27	24
24	22	28	28	28	
26	23	29	(29)?	29	
27	24	30	30	31	
29	25		31		
	26				
	27				
	28				
	29				
	30				
	31				
Total Days 25	31	24	25	24	21
Per Cent of Days 83	100	80	81	77	75

*One week of 200-mb charts missing.

/ / = Stormy days not used in other data.

TABLE II

Percentage of Days per Month on Which the Jet-stream Axis Was Plotted within 50, 100, or 150 Miles of Albany, N.Y., on the 200-, 300-, or 500-millibar Map

	Sept. 1952	Oct. 1952	Nov. 1952	Dec. 1952	Jan. 1953	Feb.* 1953	Average for 6 Months
Within 50 Miles	43	65	50	42	52	50	50
Within 100 Miles	63	84	73	55	71	64	69
Within 150 Miles	83	100	80	81	77	75	83

* On six days the 200-mb maps were unavailable.

TABLE III

Dates on Which the Radioactive Point Collector Current Was Believed to Indicate the Presence of the Jet Stream

Oct. 1952	Nov. 1952	Dec. 1952	Jan. 1953	Feb. 1953
1	3*	1	1	1
4	(4)?	3	2	2
5*	5	4	4	3
8	3	5*	5	5
10	10	7	(6)?	6
12	11	8	7	8
13	12	12	8*	9
14*	13	15	11*	10
15	14	16*	12	11
(16)?	16	17	13	(13)?
17	17*	18	14	14
18*	18	19	15	16
19	19	20	16	17
20	21	25	17	(20)?
21	24	26	18*	21
22	25	27	19*	(22)?
23	26	28	(21)?*	23
24	27	29	22	24
25	28	(31)?	23	25
30			24*	28
31	(29) †		25	
	(30) †		26	
			27	
			29	
			30	
			31	
Total Number of Days 20	18	18	24	17
Questionable Days 1	1	1	2	3

* Light precipitation occurred but not at time of "jet" indication.
† Instrument out of order.

TABLE IV

Dates on Which the Radioactive Collector Current Was Believed to Indicate the Presence of the Jet Stream when the Jet Axis Was Plotted Within 150 Miles of Albany, N.Y.

	Oct. 1952	Nov. 1952	Dec. 1952	Jan. 1953	Feb. 1953	
	1	3*	1	1	1	
	4	(4)?	3	2	2	
	5*	5	4	(6)?	3	
	8	8	5*	7	5	
	10	10	7	8*	6	
	12	11	9			
	13	12	15		8	
	14*	13	16*	13	10	
	15	14	17	14	11	
	(16)?	16	18	15	(13)?	
	17	17*	19	16	14	
	18*	18	20	17	16	
	19	19	25	18*	21	
	20	21	26	(19)?*	(22)?	
	21	24	27	(21)?*	23	
	22	26	28	22	24	
	23	27	(29)?	23		
	24	28	30	24*		
	25		(31)?	26		
	30			27		
	31			29		
				31		
	22	18	18	20	15	
Questionable days not used.....	1	1	2	3	2	
Total days on which the point correctly indicated presence of jet..	21	17	16	17	13	Total for 5 Months 84
Total days on which jet was plotted within 150 miles.....	29	22	23	20	18	112
Percentage of "jet" days correctly indicated by point.....	73	77	70	85	72	75

TABLE V

Frequency Table by Months Showing Relation between Radioactive Point Indications of the Jet and the Presence of the Jet Axis when It Was Plotted within 50, 100, or 150 Miles of Albany, N.Y., on the 200-, 300-, or 500-millibar Map

	Oct. 1952			Nov. 1952			Dec. 1952			Jan. 1953			Feb. 1953		
	Within			Within			Within			Within			Within		
Number of days	50	100	150	50	100	150	50	100	150	50	100	150	50	100	150
Jet plotted on maps	19	24	29	13	20	22	11	15	23	14	19	20	12	16	18
Number of these days that point indicated jet	16	17	21	11	16	17	10	11	16	14	17	17	10	12	13
(in per cent)	84	71	73	85	80	82	91	73	70	100	89	85	84	75	72
Jet plotted but no point activity	3	6	8	2	3	2	0	4	6	0	0	0	0	4	2
Point activity but no jet plotted	4	2	0	7	2	1	8	7	2	11	7	6	8	6	4

TABLE VI

Frequency Table for Total 5-month Period--
October 1952 through February 1953--
Showing Relation between Radioactive Collector Indications of the Jet
and the Presence of the Jet Axis
when It Was Plotted within 50, 100, or 150 Miles of Albany, N. Y.,
on the 200-, 300-, or 500-millibar map

	Average for 5 Months		
Number of days	Within 50 miles	Within 100 miles	Within 150 miles
Jet plotted on maps	69	94	112
Number of these days that point indicated jet	61 (89%)	73 (78%)	84 (75%)
Jet plotted but no point activity	5	17	18
Point activity but no jet plotted	38	24	13

When we consider the cases in which the jet axis was within 150 miles, it is found that the radioactive collector current correctly indicated the presence of the jet on 84 out of the 112 days, or 75 per cent of the time. The radioactive collector current trace failed to indicate the presence of the jet on 18 days and incorrectly indicated the presence of the jet on 13 other days. It might be mentioned that there were 9 days not used in the above comparisons when the positive current readings were probably high enough to indicate the jet, but when it still was questionable. Also, if we consider all the days when the jet was within 250 miles of Albany at any of the three levels we have used, it is found that the radioactive collector failed to indicate the presence of the jet on three days (January 4,5, and 25).

Data in the previous tables were based on the distance from Albany to the nearest jet-stream axis. Since the band of high-velocity winds is certainly wider than the indicated axis line on the maps, it probably would have been better to use the distance to the first isotach line enclosing the jet axis. This should make the previous correlation somewhat better.

As a check on this, all the days on which the radioactive collector showed the highest fair-weather currents (well above 0.05 microampere for 6 to 12 hours or more) were picked out; there were 50 such days in the five-month period. Upper-air charts for these days were then examined, and the distances from Albany to the region of highest winds along the jet-stream axis were noted. Table VII shows the results of these comparisons. On 42 out of the 50, or on 80 per cent of the days, Albany was within the band of highest winds along the jet axis. On 46 out of the 50 days, winds were 80 knots or more over Albany, and on 28 days they were 100 knots or more. On two successive days in November 1951, current readings were exceptionally high during the night and morning, and at the same time there was a dense fog. There was, however, a 60- to 80-knot jet indicated right over Albany on both occasions.

It is realized that the exact position of the jet-stream axis as drawn on the upper-air charts is of doubtful accuracy on many occasions, since reliable data in a fine enough network to detect a narrow band of high-velocity winds are not available to the map plotters at present. It is felt that on several occasions when the jet was not plotted over the area, although the electrical activity indicated that it should be, the maps were in error--owing to lack of sufficient information. On several of these days of high electrical activity with no jet indicated on the maps, typical jet-stream clouds, as described[4] by Schaefer in Stockholm and

(4) Schaefer, Vincent J., "Clouds of the Jet Stream," Tellus, 5, 27-31 (1953).

TABLE VII

Dates on Which Radioactive Collector Currents Were Highest for 6 to 12 Hours or More and the Number of These Days on Which the Jet-stream Winds over Albany Were of Certain Indicated Velocities at the Level of Highest Winds

	Oct. 1952	Nov. 1952	Dec. 1952	Jan. 1953	Feb. 1953	Total for 5 Months
	8	3	4	4	1	
	10	5	7	5	7	
	14	8	8	7	8	
	15	10	16	12	9	
	16	12	17	14	10	
	17	16	18	15	16	
	24	17	19	16	17	
	25	19	26	17	18	
		27	27	25	25	
		28	28	26		
			29	27		
				31		
Total Days	8	10	11	12	9	50
Days with Indicated Winds of						
60 knots	0	1	2	1	0	4
80 knots	2	2	5	6	0	15
90 knots	0	2	0	1	0	3
100 knots	2	3	4	2	3	14
120 knots	2	2	0	0	5	9
130 knots	0	0	0	0	1	1
140 knots	2	0	0	2	0	4

On 42, or 80 per cent, of all days with highest electrical activity, the band of jet-stream winds was right over the Albany-Schenectady area. On 46 days the winds were 80 knots or greater; on 28 days they were 100 knots or greater; and on 14 days they were 120 knots or greater.

at the New York American Meteorological Society meeting last January, were observed. On such occasions, we often find from nephoscope readings of the cirrus clouds that higher velocities exist at the cloud level than are indicated on the isotach charts. On many of these occasions, we believe that we may be detecting the presence of a so-called "jet streak."

The apparently good correlation between fair-weather electrical activity and the jet stream discussed above is, of course, based on observations made at Schenectady and may be different at other locations. The limiting current values for determining jet activity are likely to be somewhat different at other locations, depending upon such things as the height of the collector above ground and its proximity to other objects or structures. However, field tests with a portable radioactive point and an ultrasensitive d-c microammeter show that the current indicated by a point held 15 to 20 feet above the ground runs about 0.01 to 0.02 microampere less than that obtained at the same time from a similar point collector located on our laboratory roof 90 feet or so above the ground.

Why is there an apparent relation between atmospheric electrical activity and the jet stream?

First of all, we should consider the possibility that, because a jet stream is over the Schenectady area at some level a large part of the time, there would automatically be a good correlation if there were also a large number of jet days indicated by the radioactive collector.

In using radium as the radioactive material, we may be experiencing difficulties with β- and γ-rays as discussed by Chalmers in his book on atmospheric electricity.(5) Although there is a fairly direct effect of local wind variations on the current readings when velocities are below 8 or 10 miles per hour, at higher velocities the currents may or may not show a direct relation to the surface wind. It can only be said that for the purposes for which we have been using this type of collector the over-all results seem quite consistent, and it is believed that the major changes in the electrical field are indicated quite clearly.

There is one other consideration that may be confusing our observations: on a large number of days when the fair-weather currents were high, the relative humidity was low. This condition, of course, usually exists in fair weather anyway, but it is also true that conductivity

(5) Chalmers, J.A., Atmospheric Electricity, Oxford University Press (1949), pp. 53-54.

of the air is usually greater on clear days with low moisture content of the air. However, it is not quite clear why a jet stream should always be near on days of low relative humidity.

If the radioactive collector is indicating variations of the fair-weather field--as presumably it is--then on clear dry days when conductivity is greater the field should be lower. This is the opposite effect from what we observe and lends further support to the belief that there is an increase in the positive fair-weather field underneath the region of jet-stream winds aloft.

In spite of the previous considerations, which could account for some of the higher fair-weather fields, it is the feeling of the author that these electrical effects are definitely associated with the jet stream for the following reasons. It is noted that a jet in traveling over the earth will pass over regions of stormy weather, as well as fair weather. In fact, a jet stream is usually found in the vicinity of heavy thunderstorms or other stormy areas, including tornadoes.

If we accept C.T.R. Wilson's theory(6) that the electrical activity associated with thunderstorms produces a separation of charge such that the earth regains a negative charge while the high atmosphere receives an equivalent amount of positive charge, it may be that some of this positive charge could be picked up by a passing narrow band of high-velocity wind and this charge could be carried out with the jet winds to a fair-weather area and there increase the positive field already existing. A timely article as far as this paper is concerned appears in the April 1953 issue of the Scientific American. On pages 34 and 35 there appears a drawing which illustrates Wilson's theory of how the earth's charge is maintained. If the streams of positive current flow out of the thunderstorm areas were labeled "jet stream," it would serve as an excellent illustration for this paper. Even if there are no thunderstorms, a considerable positive charge is likely to develop in the upper portion of an otherwise heavy storm area which would be subject to the same transfer of charge from the stormy area to a fair-weather area by means of the jet stream.

Some evidence in support of this is recalled from previous observations using a nonradioactive point collector when it was noted by Schaefer(7) and Falconer(1) that small positive pips often occurred

(6) Wilson, C.T.R., Compendium of Meteorology (1951), p. 113.
(7) Schaefer, Vincent J., "Properties of Particles of Snow and the Electrical Effects They Produce in Storms," Trans. Am. Geophys. Union, 28, 587 (1947).

on the record chart from 6 to 12 hours or so preceding the arrival of precipitation. We now observe with the radioactive collector that fair weather currents are generally high preceding the arrival of major precipitation. This is particularly true when a jet stream moves in from the south or southwest. When a jet moves down from the northwest or north, it is more apt to maintain fair cool weather over the area.

The possibility should not be overlooked that the Simpson-Scrase ice-friction theory[2] might contribute additional charge of the right sign to further increase the fair-weather field. This would have some definite possibility if we consider the fact that cirrus or ice-crystal haze is much more common in the high atmosphere than can be detected from the ground,[3] as discussed earlier. Certainly there is enough wind shear, turbulence, etc., associated with the jet stream to create considerable friction among any existing ice crystals.

On February 21 and 22, 1953, the jet stream was indicated within 50 miles of Schenectady at all levels and with winds from 100 to 160 knots from the southwest. The electrical activity even with clear skies was too low to safely say that the jet was indicated by this means. However, unless there were some undetectable difficulties with the amplifier, one possible reason may have been the severe duststorms in the Southwest that occurred on February 16 and 19. Duststorms are known to produce negative fields and, therefore, if large quantities of highly electrified dust get into the high atmosphere, it may tend to neutralize an otherwise large positive field.

Now, if the jet-stream winds really do carry higher positive charges acquired because the jet stream has previously passed over a stormy area, it may be that this additional charge contributes to the triggering off of some thunderstorms and tornadoes, since the jet stream is usually associated with these phenomena.

In conclusion, then, it seems to the author that there may be an electrical effect associated with the jet stream which can be readily detected by as simple a device as a radioactive collector and a suitable sensitive current indicator or recorder.

However, before definite conclusions are drawn, observations at other locations around the country should be made to determine more definitely whether the electrical effects observed at Schenectady apply generally. It is suggested that a network of such instruments might be useful for continuously checking on the location of jet streams. Such information might be useful in detecting the possibilities of tornadoes, thunderstorms, turbulence, and general precipitation, since all appear to be related to the effects of the jet stream.

The author has now found that a General Electric photoelectric recorder having a sensitivity of 0.266 microampere shunted to read 0.50 microampere full scale is about the right sensitivity to use. Such a recorder was recently installed; it eliminates the need for an electrometer, which tends to drift and cause misleading results unless a frequent zero check is maintained.

The radioactive collector and recorder combination would probably cost in the neighborhood of $800 or $900. Although the recorder would be most desirable, cost might prohibit its general use. There is, however, an ultrasensitive d-c microammeter on the market which with the radioactive collector might cost $150 to $200. Readings on the meter every hour or so would give some idea of the magnitude of the fair-weather current, and any general increases due to the jet stream could be readily detected.

It is not presumed that the results presented here prove conclusively that a relation exists between atmospheric electrical activity and the jet stream. However, in view of the present-day interest in the jet stream and the ways of detecting it, it was thought that our findings at Schenectady should be made known as soon as possible, with the hope that similar observations might be made in other parts of the country. If the relation is real, then such observations made regularly at many points should be of great value to forecasters and others concerned with high-velocity winds in the high atmosphere.

ACKNOWLEDGMENTS

The author gratefully acknowledges the cooperation of Harry Wexler and Ernest Christie of the U.S. Weather Bureau for making available the upper-air maps used in this work. He is greatly indebted to Vincent Schaefer for many helpful suggestions and encouragement in this work, and to Kiah Maynard, who greatly assisted in the work in many ways.

Part 2

THE CONCENTRATION OF ICE NUCLEI IN AIR PASSING THE SUMMIT OF MT. WASHINGTON

Vincent J. Schaefer

Among the variable factors affecting atmospheric processes is the presence or absence of ice-crystal nuclei. Despite the obvious importance of these microscopic particles to the Bergeron-Findeisen precipitation mechanism, relatively little is known about the probable sources of supply of such particles, the variation in their relative concentrations in the atmosphere, or their potential importance in affecting the development of storm systems. Methods for detecting them have been described.(1)

Early in the field-research program of Project Cirrus, it was decided to initiate regular observations of ice-crystal-nuclei concentrations at the summit of Mt. Washington. This location in northern New Hampshire at an elevation of 6288 feet above sea level was selected for several reasons. It was the only available location where suitable accompanying weather data could be obtained at a high-altitude station; it was the highest spot in the northeastern United States; reliable observations could be expected from personnel of the Mt. Washington Observatory; and there was a good opportunity of having relative freedom from industrial pollution during many observations.

INSTRUMENTATION FOR ICE-NUCLEI OBSERVATIONS

While it is desirable to make measurements of ice-nuclei concentrations at several temperatures below freezing, it was decided for the sake of simplicity to use only one temperature--that of the lowest temperature obtainable with the cold chamber available. This turned out to be the range between -16° and -20°C. The majority of observations were made at -18°C.

For the sake of reliability and simplicity, it was decided to adopt an observational procedure that would be easy to carry out and would tend to eliminate subjective errors due to changes in personnel. It is believed that these efforts have been reasonably successful during the nearly six years of observational experience.

Preceding Page Blank

The detailed procedures for making observations are published in several available reports. The cold chamber used is illustrated schematically in Fig. 1. One of its most important features is a lining of black chiffon velvet mounted about 1/2 inch from the frosty walls of the chamber. The porous nature of the cloth permits reasonably good heat transfer but prevents the movement into the observational area of fragmentation nuclei consisting of broken frost particles. Since the walls of the chamber are the coldest part of the test unit, the velvet lining remains frost-free for long periods of time.

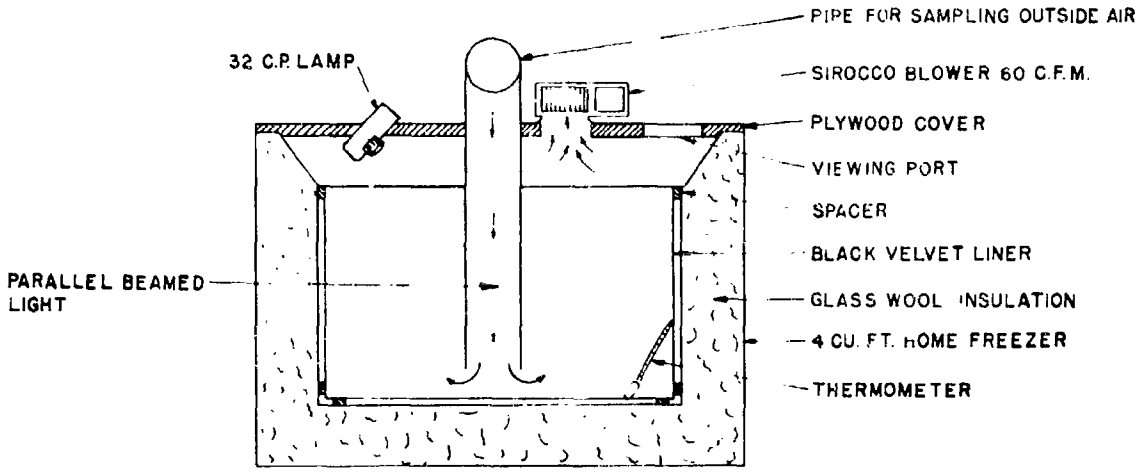


Fig. 1 Cold chamber for detecting sublimation nuclei.

PROCEDURE FOR MAKING ICE-NUCLEI OBSERVATIONS

In making an observation of the number of nuclei in the air passing by the mountain summit, a sample of air is drawn in from the outside of the Observatory by a sirocco blower. After the sample is brought into the box, it is permitted to remain quiet for a minute or so. This is to assure that any ice crystals contained in the air have a chance to settle to the bottom of the chamber. A supercooled cloud is then formed and the number of ice crystals that appear in the cloud is estimated. A narrow, concentrated beam of light illuminates a total volume of about 1 liter of air in the box and is used for estimating the ice-crystal concentration.

If the concentration of ice crystals is high, an estimate of the concentration is made by determining the distance that separates the individual crystals from each other. Thus, if the average distance is 1 cm,

a value of 1 crystal per cubic centimeter is recorded. If the concentration is less, the number seen at a given instant in the beam is recorded. Thus, if an average of 10 crystals per beam is seen as the air is stirred in the chamber, this is equivalent to 10 per liter or 1×10^4 per cubic meter. When the number of crystals is very low, the total number seen during a period of two minutes is noted. Since the working volume of the chamber is approximately 100 liters, if 10 crystals are seen during the two-minute period a value of 1×10^2 crystals per cubic meter is given.

This relatively crude method of semiquantitative observation seems to be justified because of the large variations that occur in the normal concentration of ice nuclei. A better method would be needed if the variations covered only a few orders of magnitude. Actually, more than a million-fold variation in the concentration of ice nuclei is of common occurrence.

Since the major objective of the ice-nuclei studies was to obtain a rough idea of the variations that occur at a specific location as a function of weather types, wind direction and velocity, air trajectory, seasonal change, and similar phenomena, it was decided for purposes of keeping a running analysis to segregate the observational values into the following three categories:

1. "low counts," covering the range from 0 to 500 crystals per cubic meter,

2. "high counts," representing the range from one crystal in two cubic centimeters to 10 or more per cubic centimeter or 500,000 to 10,000,000 per cubic meter,

3. "moderate counts," representing values in between or from 500 to 500,000 per cubic meter.

YEARLY VARIATIONS IN ICE-NUCLEI CONCENTRATIONS

By expressing the monthly totals of these three ranges of nuclei concentration as percentages, the observations made during a specific month may be plotted so that periodic fluctuations in relative concentrations are disclosed. This has been done and is presented as Fig. 2.

An interesting feature of this graph is the yearly fluctuation in relative nuclei concentrations which between 1949 and 1952 showed a maximum of low-point values during the June, July, and August quarter of the year, and minimum values starting about December.

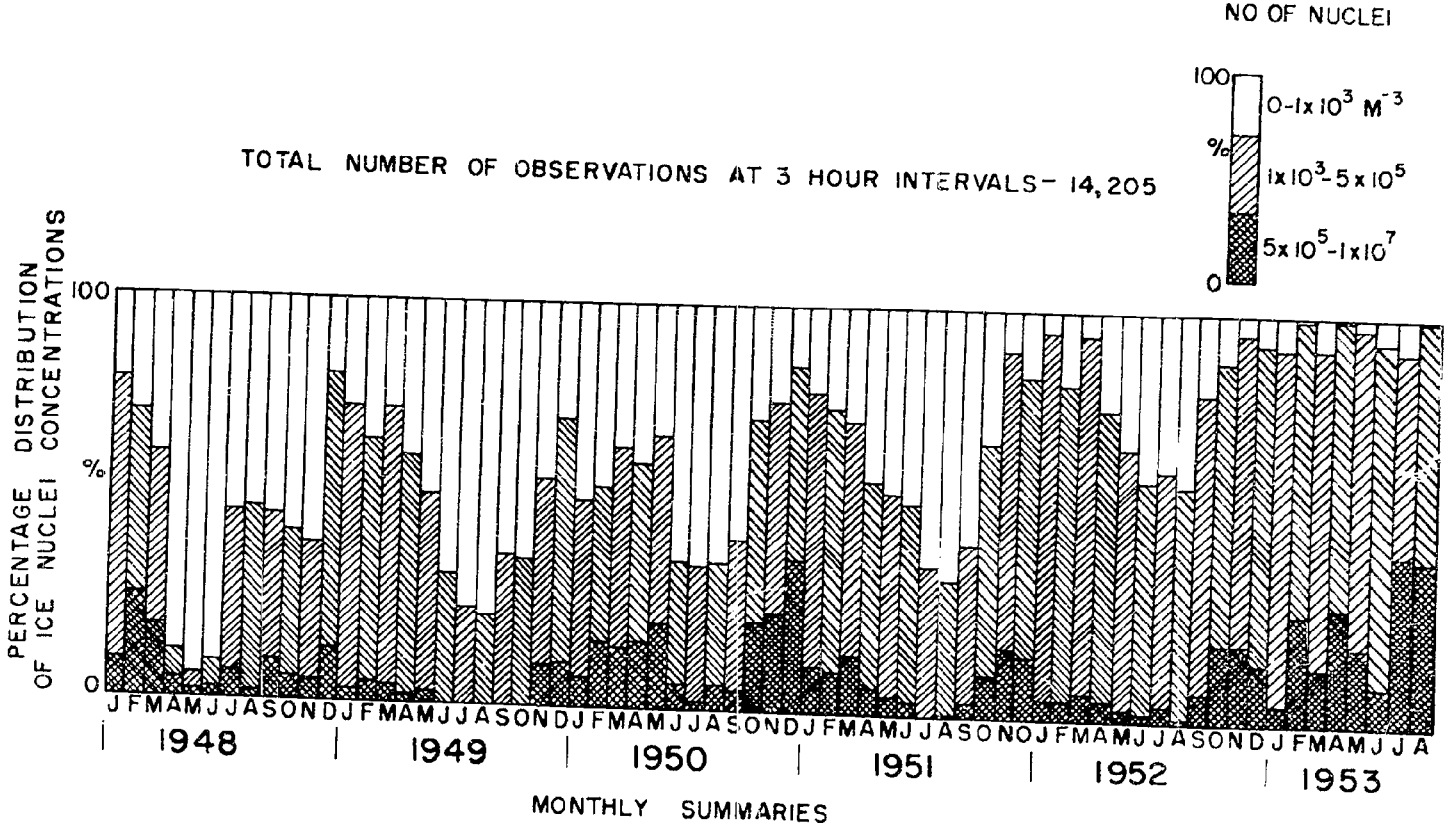


Fig. 2 Ice nuclei concentrations at summit of Mt. Washington.

The more than 15,000 separate observations that have been taken on a three-hourly day-and-night schedule throughout the year represent a unique series of such records.

A number of studies have been made of these data to determine possible relationships of air movements and synoptic weather developments that might be associated. These have been published in three Project Cirrus reports.[2-4] A typical chart showing several air trajectories related to high-count periods is included as Fig. 3.

ANOMALOUS RECORD DURING 1953 PERIOD

A quick glance at Fig. 2 discloses a trend toward higher values starting in the early part of 1950. Each successive year showed the period of maximum low count in the summer months to be less pronounced, until in 1953 it had nearly disappeared. In fact, July and August showed the highest percentage of "high counts" for any time in the year during the preceding 66 months, and the lowest percentage of "low counts" in 58 months!

Perhaps this anomaly is reflecting the great drought of the Southwest, which has been successively worse during the years since 1950.

In the earlier studies cited, rough trajectories were drawn for all of the outstanding high-count periods for which meteorological data could be obtained. These corroborated an earlier hypothesis that the main source of ice-crystal nuclei in the northeastern United States resided in soil airborne from the semi-arid regions of the West. The ultimate source of many of these aerosols is of volcanic origin. It is easily established that many of the residues from volcanic eruptions, whether from fossil layers or from more recent deposits, are very good as ice-crystal nuclei. One of the most effective sources of foreign-particle ice-crystal nuclei was a sample of volcanic ash collected in the saddle between Mauna Kea and Mauna Loa in the Hawaiian Islands. This sample showed a threshold of activity of -16°C with about 50 per cent of the particles active at -22°C. It was quite similar in this respect to the sample obtained from the much earlier deposits of Crater Lake, which was previously cited.

On May 1, 1953, a "mudfall" occurred at Schenectady, starting about 1700 and continuing until 1000 the following day during a drizzling rainfall. Preceding this storm were spectacular displays of jet stream

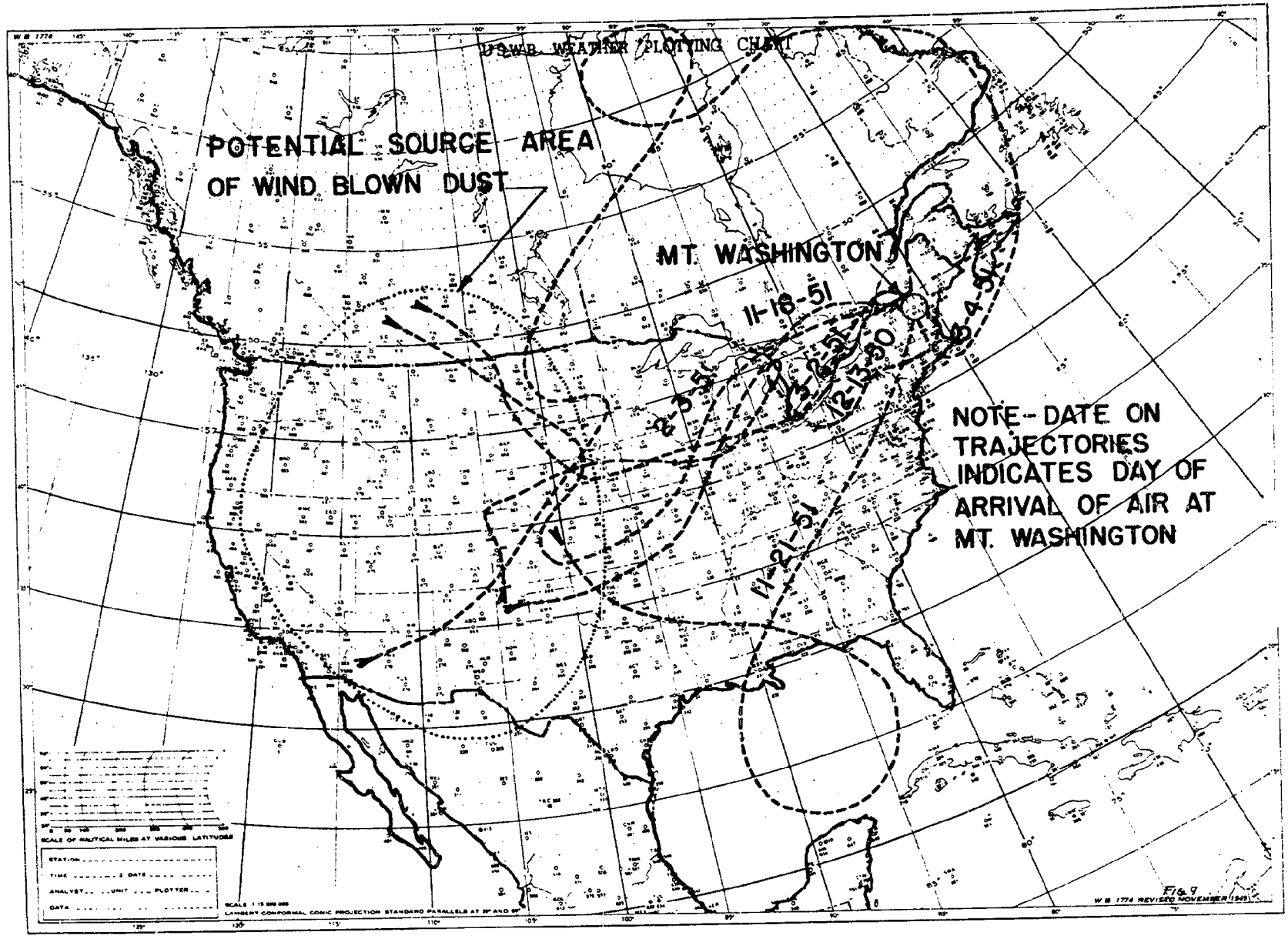


Fig. 3 Trajectories of air reaching Mt. Washington during four periods when concentration of ice nuclei showed high values.

clouds from the west. These had a trajectory from the southwest. A rough estimate of the amount of airborne soil that fell in eastern New York during this period showed that the deposit amounted to approximately 200 tons per square mile. When sediment was collected on clean glass plates, dried, and dusted into a cold chamber, many ice crystals formed on the particles at -20°C. This mudfall was probably related to the dust storms that were occurring in the Panhandle region of Texas and Oklahoma. These were related to a jet stream which at 40,000 feet was indicated to have a velocity in excess of 120 knots.

A study of the ice-nuclei data from Mt. Washington shows that a high-count period starting April 26 continued at high levels until May 4 and then dropped to lower values, which persisted until May 22.

Such observations are typical of a number that may be correlated with the variations in ice-nuclei concentration. Much more research should be conducted in this interesting field. A network of cooperative stations should be established to learn more about the variabilities that probably occur.

On the basis of the studies that have been made of the Mt. Washington data contained in considerable detail in the three reports issued by Project Cirrus, the following conclusions have been drawn, based on more than 14,000 individual observations.

1. The concentration of foreign-particle ice-nuclei effective in air having a temperature of -20°C passing the summit of Mt. Washington varies by a factor of a million.

2. The highest concentration of such nuclei thus far observed is of the order of 1×10^7 per m^3 or 10 per cm^3. [Note: A concentration in excess of 5×10^7 m^{-3} (50 per cm^3) is required to cause the complete evaporation of water droplets in a supercooled cloud within a minute.]

3. It is not uncommon to find a complete absence of ice-crystal nuclei at -20°C.

4. When exceptionally high concentrations of nuclei occur, they tend to persist for periods of six to sixty hours.

5. A study of such high-count periods shows that in most cases the air passing the summit of Mt. Washington had a trajectory from the semi-arid regions of the West. In many cases, the high-count periods coincided with the presence of a jet stream in the immediate vicinity of the mountain. The fact that dust storms in the West often occur at the time a high-velocity jet stream is overhead indicates the strong probability of an interrelationship between dust storms, jet streams, and high concentrations of foreign-particle ice nuclei.

6. From January 1948 until May 1952, about half of the observations showed concentrations less than 500 crystals per cubic meter. From May 1952 to July 1953, an entirely new pattern developed in which less than 14 per cent showed the low values.

7. From January 1948 until January 1953, a very definite seasonal fluctuation in nuclei is noted, with the highest concentrations appearing in the winter months and the lowest values in the summer. This decrease in the summer failed to appear in 1953.

8. In 1949, a trend is noticed toward higher values for foreign-particle ice nuclei, with each low period higher than the preceding year. The anomaly in 1953 may be a reflection of this trend. It is quite possible that these higher values are related to the intensification and enlargement of the drought region in the southwestern states.

9. The Mt. Washington data show conclusively that the concentration of foreign-particle ice-crystal nuclei varies over wide limits and that periods occur in which there are not enough in the air to initiate the precipitation cycle by the ice-crystal process, even if suitable conditions were to develop. This is reflected in the current findings of research workers that the Bergeron-Findeisen precipitation mechanism is not so

important as once believed in the initiation of precipitation in many types of clouds. This does not mean that ice crystals are not important factors in atmospheric processes. In fact, it suggests a reason why storms sometimes behave in an abnormal fashion. It also indicates that important new discoveries in the field of meteorology will follow intelligent application of cloud-seeding techniques.

ACKNOWLEDGMENTS

The writer wishes to extend sincere thanks to the personnel of the Mt. Washington Observatory responsible for securing the basic observations about which this paper is written. Thanks are due also to H. J. Wells, AGC, USN, who prepared many analyses of air trajectories; to Lt. Comdr. William E. Hubert, who with Wells made a study of the relationship of synoptic weather to the variations in nuclei concentrations; and to R. E. Falconer and K. Maynard, who provided related weather data and assisted in compiling some of the statistical studies on which some of the conclusions are based.

REFERENCES

1. Schaefer, V. J., "The Detection of Ice Nuclei in the Free Atmosphere," Meteorol., 6, 283 (1949).

2. Schaefer, V. J., "The Occurrence of Ice Crystal Nuclei in the Free Atmosphere," Proc. First Nat'l Air Pollution Symposium, Stanford Research Institute, Pasadena, California (1950).

3. Hubert, W. E., and Wells, H. J., "Concentration of Ice Crystal Nuclei under Various Weather Conditions," Project Cirrus Occasional Report No. 28, G-E Research Lab. Rept. No. RL-541 (June 1951).

4. Schaefer, V. J., "The Concentration of Ice Nuclei at the Summit of Mt. Washington," Project Cirrus Occasional Report No. 35, G-E Research Lab. Rept. No. RL-722 (August 1952).

Part 3

ICE CRYSTALS FORMED SPONTANEOUSLY BY THE RAPID EXPANSION OF MOIST AIR

Vincent J. Schaefer

The formation of large concentrations of ice crystals from vortices induced by aircraft propellers and wings is of common occurrence, although these are not often noticed because of the fleeting nature of the phenomenon.

During some of the early laboratory work of Project Cirrus, Vonnegut described[1] a few simple experiments illustrating the ease with which ice crystals may be formed under suitable conditions of rapid adiabatic expansive cooling. A short while later, the writer made a brief investigation of this effect and more recently concluded a series of experiments designed to explore some of the quantitative relationships between moisture, pressure, and humidity. Several methods were used for conducting these experiments.

One of these consisted of a copper cylinder that could be capped, pressurized, the absolute humidity of the air controlled, and then the pressure released suddenly by a trigger device. A much simpler but equally effective method made use of a small, thin-walled glass bulb, which, after being pressurized, could be broken suddenly with a falling weight. This latter method will be described in detail since it produced results similar to those obtained with the more elaborate equipment.

THE GLASS-SPHERE METHOD FOR PRODUCING LARGE NUMBERS OF ICE CRYSTALS

A 10-inch length of Pyrex glass tubing, 0.167 inch OD, 0.075 inch ID, was heated in cross flames until one end closed. This was then blown into a bulb 0.225 inch in diameter with walls about 0.015 inch thick. One and one-half inches of tubing was left attached to the glass sphere. A small brass rod was turned to make a slide fit in the bore of the tube. One end was turned to a diameter of 0.140 inch, so that, when placed against the end of the 1-1/2-inch length of glass tube, its small end did not project into the interior of the bulb but was flush with its inside surface. A small slot cut along the length of the brass rod with a jeweler's saw served as an air leak during pressurization and limited the flow down the tube after

breakage. A copper tube with high-pressure connections using about two inches of high-pressure plastic tubing was used to connect the air line to the small sphere. The bulb as used had a volume capacity of approximately 1×10^{-1} cm^3.

Humidity under most conditions of the experiment was obtained by establishing equilibrium with respect to ice at a specific temperature. This was accomplished by injecting enough water into the bulb with a micropipette to coat the bulb's interior with a thin layer of water. This was then frozen.

For making a run at a specific temperature, a copper block was machined to accommodate the glass bulb in a suitable position for cooling, breaking, and permitting the pressurized air to escape into the surroundings without delay. The unit is shown as Fig. 1.

The copper block was fashioned as an integral part of the breaking mechanism and made small enough to be conveniently raised and lowered in a cold chamber. A brass block 10 cm by 2.5 cm by 1.25 cm with a hardened-steel point projecting from its lower surface, was raised 50 cm to the top of two guide shafts and then suddenly released. Upon falling, the steel point impinged upon the glass bulb and shattered it. The expanding air then shot rapidly outward from the cavity into the surrounding air of the cold chamber.

A cold chamber of 100 liters' capacity was used in all experiments. It was operated at an equilibrium temperature of -14°C, $\pm$ 1°, with a continuous supply of moist air feeding into it and forming a supercooled cloud.(2) Under such conditions, ice crystals have a highly favorable environment for continuing growth, since at -14°C the differential of the partial vapor pressures of ice and water reaches a maximum value.

THE RESULTS OF GENERATING ICE CRYSTALS BY THE RAPID EXPANSION OF MOIST AIR

In the series of experiments to be described, six different pressures and three different temperatures were used. After the crystals were generated by the sudden expansion of the compressed air, the number formed in this manner was estimated by a procedure, described by the writer,(3) involving the rate of fall-out of ice crystals being fed moisture at a constant rate.

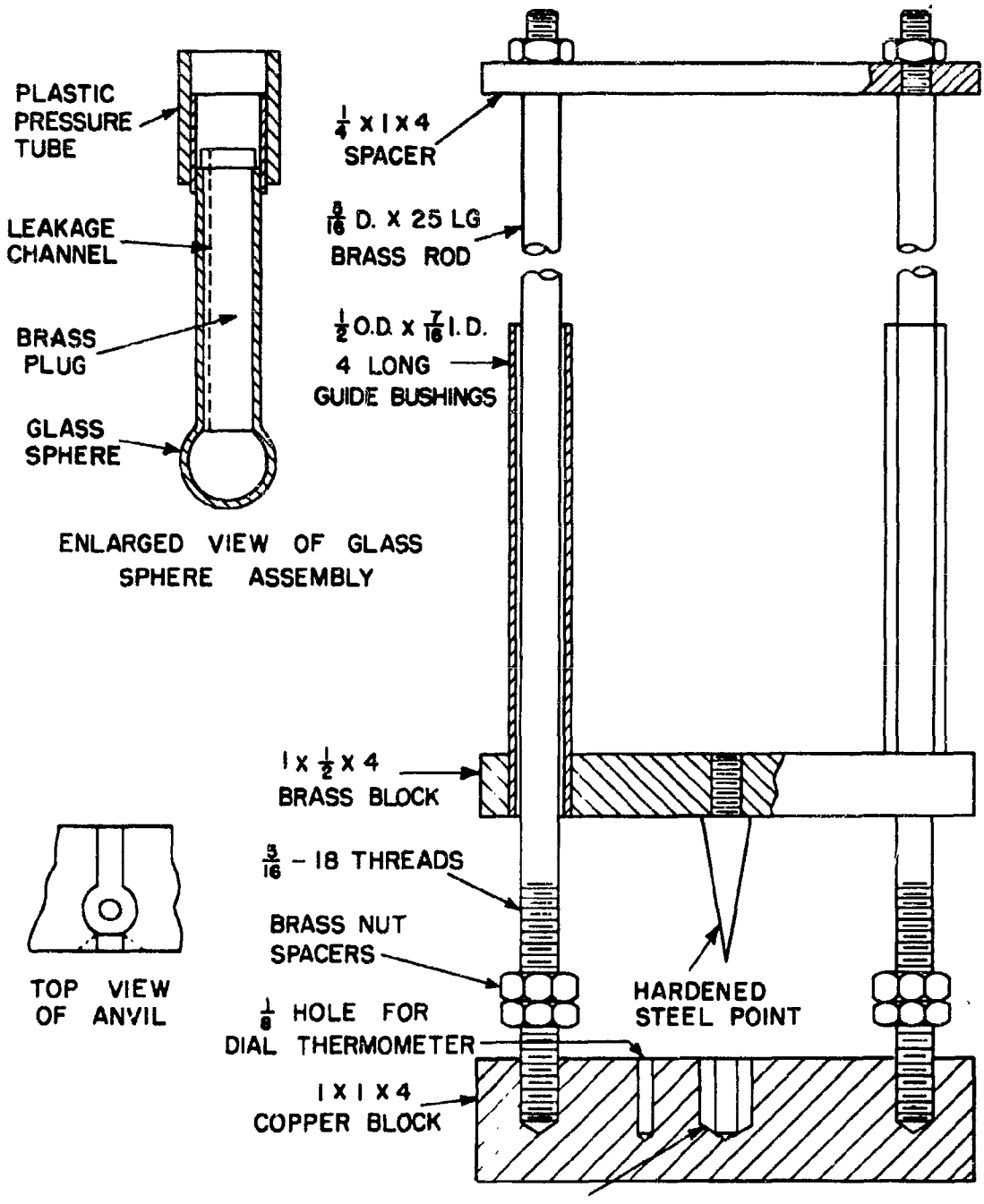


Fig. 1 Apparatus for generating ice crystals by rapid expansion of pressurized moist air.

An entirely different method was used in earlier experiments. The earlier method gave similar values but was not so convenient; also, it required greater experimental skill and more equipment. This method utilized two cold chambers. The ice crystals were generated in the first chamber, which had a volume of 50 liters. Immediately following the generation of ice crystals by expansion, a known volume of the highly concentrated mass of crystals was rapidly transported from the 50-liter chamber to another having a capacity of 100 liters. Both chambers contained supercooled clouds. The small but highly concentrated mass of crystals spreading through the second chamber became sufficiently diluted that their concentration was low enough to prevent further evaporation of the smaller crystals, and far enough apart to permit the concentration to be estimated. By measuring this concentration in the second chamber, and knowing the fraction of the volume removed from the first chamber, it was possible to determine the initial concentration of crystals to a reasonable degree of accuracy.

It is important to realize that, in all cases described, the values given represent a low limit of the initial concentration. Evaporation, coagulation, melting, and other effects may have reduced the observed values by several orders of magnitude.

THE CONCENTRATION OF ICE CRYSTALS OBSERVED

As shown by Fig. 2, an upper limit to the number of ice crystals that may be produced by expansion cooling seems to lie in the range of $1 \times 10^{11}/cm^3$. The actual value of the concentration of primary nuclei might be ten to one hundred or more times greater than this concentration for the reasons mentioned.

Even though this observed value of 1×10^{11} crystals per cubic centimeter represented the maximum number that could be formed by rapid adiabatic expansive cooling, the fact that it is possible to form such tremendous numbers of ice crystals in pure air is of great significance. It becomes obvious that a mechanism is involved that does not rely on foreign-particle nuclei to serve as centers of formation. Of even greater significance is the sharp break that occurs in the curve shown in the figure. This indicates that a sharp discontinuity occurs in the physical relationships causing this phenomenon. While it has not thus far been possible to firmly establish the physical mechanism responsible for the formation of such a tremendous initial concentration of ice-crystal nuclei, other experiments give strong clues in this direction. The dry-ice effect, originally reported by the writer[4] and more

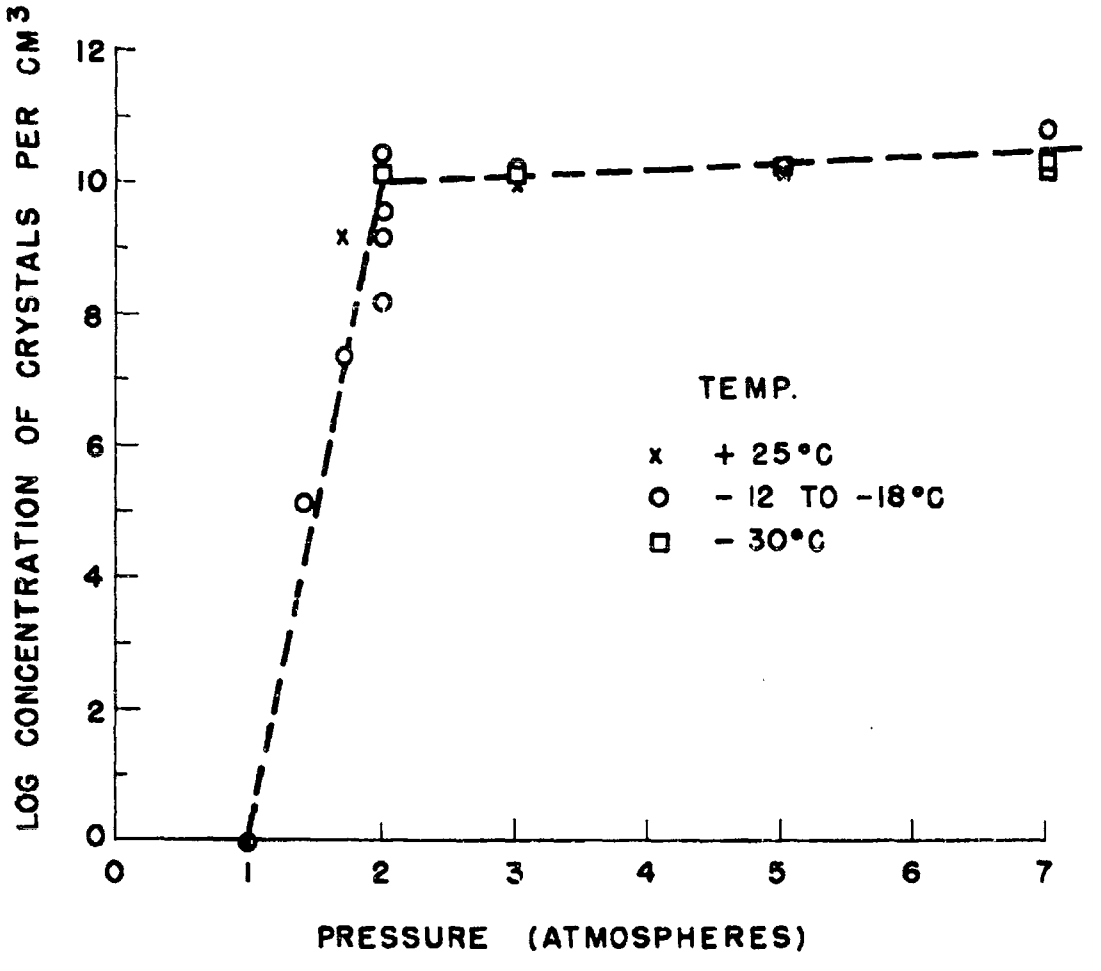


Fig. 2 Concentration of ice crystals formed spontaneously by sudden expansion of air as related to temperature, moisture and pressure.

recently studied in detail with the continuous cloud chamber,(5) suggests that the spontaneous formation of ice crystals occurs only when air contains moisture equivalent to water saturation at -39°C and the air cools to at least that temperature. Under such conditions, submicroscopic ice crystals form in great number. If they are surrounded by air supersaturated with respect to ice, those that exceed a critical size continue to grow by the vapor-diffusion process.

A study of Fig. 2 and Table I shows that the number of ice-crystal nuclei that form spontaneously and grow as moist air is cooled rapidly by adiabatic expansion tends to reach a limiting value. Once

this concentration is reached, a moisture increase of four orders of magnitude, a doubling of the pressure, or a decrease in temperature of more than 30°C, has little effect on raising this value. Thus, at a pressure of 60 psi, an increase in moisture of more than a hundredfold only doubles the number of crystals observed. Two runs with the same amount of moisture but with pressures of 15 and 90 psi gave values of 4.3×10^{10} and 3.0×10^{10} crystals per cm^3, respectively. Similarly, an initial temperature of -12°C and 30 psi compared with -38°C and 90 psi resulted in only doubling the concentration.

TABLE I

Data Obtained under Several Conditions of Temperature and Pressure

Pressure, psi	Bulb Temp, °C	Available Moisture, g/ccm x 10^{-6}	Crystals Formed, N/cm^3
3	-18	0.923	2.7×10^3
6	-12	1.673	1.1×10^5
10	+25	23.063	1.5×10^9
10	-15	1.303	3.3×10^7
15	-15	1.303	1.5×10^9
15	-18	0.923	5.5×10^9
15	-19	0.863	1.6×10^8
15	-20	0.755	4.3×10^{10}
15	-30	0.203	1.4×10^{10}
30	+25	23.063	9.6×10^9
30	-12	1.673	2.3×10^{10}
30	-30	0.203	1.3×10^{10}
60	+25	23.063	5.8×10^{10}
60	-15	1.303	2.6×10^{10}
60	-30	0.203	2.0×10^{10}
60	-30	0.203	2.1×10^{10}
90	-17	1.063	1.4×10^{10}
90	-18	0.923	8.0×10^{10}
90	-20	0.755	3.0×10^{10}
90	-38	0.014	5.1×10^{10}

These effects are probably due to the following factors.

1. A critical reaction occurs.

2. The conditions necessary to produce this effect are pressures in excess of 10 psi above atmospheric pressure, with the air containing enough moisture that, when it is cooled below -39°C, supersaturation is sufficient to cause the spontaneous formation of submicroscopic water droplets in high concentration.

3. The number of ice crystals that form is dependent on the particles that survive by growing larger than a critical size during the expansion cycle (a few milliseconds) and that then enter an environment conducive to their continued growth. This latter condition is best achieved by surrounding the experimental area with a supercooled cloud having a temperature colder than -10°C.

By several entirely different types of experiments, which have been mentioned previously, the existence of a critical phenomenon at -39°C has been established. With the continuous cloud chamber, it has been shown experimentally that not only do all pure water droplets freeze at -39°C but they may produce additional new crystals when the air is saturated with respect to water.

A simple calculation has been made using the highest value of ice-crystal concentration observed in the current series of experiments to establish the probable size of the crystals that must form by this rapid expansion method. The calculation assumes that all of the moisture available is used in forming the crystals and that they are the survivors of the reaction which occurs at -39°C.

The experiment used a glass sphere cooled to -38°C and lined with a thin layer of ice. The amount of moisture contained in the sphere was equivalent to 1.4×10^{-8} g per cm^3. The sphere was pressurized to 90 psi. After the sphere was broken, the crystals passed into an environment containing a supercooled cloud at -22°C. Following the dilution and growth of the crystals, the number that formed was determined semiquantitatively to be 5×10^{10} per cubic centimeter. This

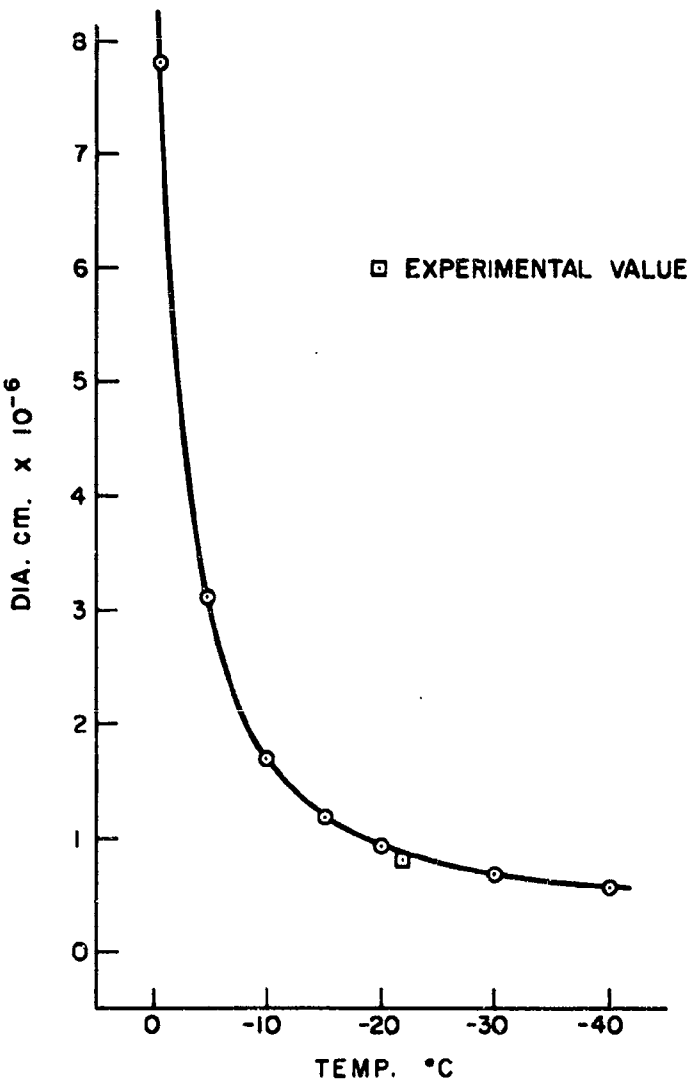


Fig. 3 The relationship of critical size of ice nuclei to temperature.

number divided into the weight of available moisture indicates an amount of water per crystal of 2.8×10^{-19} gram. By using Avogadro's number and the molecular weight of water, this value would indicate that the average number of molecules is 9300 per crystal. Assuming that the surviving particle would initially be spherical, this would indicate a diameter of 81 A.

In some of our earlier studies, Langmuir calculated[6] the critical-size limit of ice crystals that would survive under various physical conditions. This relationship is shown in Fig. 3. The nearly perfect agreement of the example cited with this curve may be fortuitous, but it indicates that the experimental results are of the right order of magnitude.

While these experiments do not establish the size of the spontaneously formed primary ice nucleus, they show that the practical limit to the number of ice crystals that may be produced by rapid adiabatic expansion in a unit volume of moist air is governed by the number of those that grow larger than a critical size after the air is cooled below -39°C. This size is a function of temperature and moisture and approaches a limiting value of 50 A (0.005μ) in diameter at -40°C.

Much work remains to be done in exploring these relationships. For example, it was discovered just at the conclusion of the experiments described in this paper that it was possible to produce ice crystals continuously by the rapid expansion of moist air from a high-pressure air source. Moist air under 90 psi pressure emerging from an orifice having a hole 100 microns in diameter formed a dense fog of ice crystals. These caused an optical effect, indicating the particles to be less than 0.1 micron in diameter.

By using this continuous-flow process for generating ice crystals, it should be feasible to the complete range of ice-crystal nucleation due to the rapid expansion cooling of moist air.

REFERENCES

1. Vonnegut, B., "The Production of Ice Crystals by the Adiabatic Expansion of Gas," J. Applied Phys., 19, 959 (1948).

2. Schaefer, V.J., "The Production of Clouds Containing Supercooled Water Droplets or Ice Crystals Under Laboratory Conditions," Bull. Am. Meteor. Soc., 29, 175 (1948).

3. Schaefer, V.J., "The Measurement of High Concentrations of Ice Nuclei in a Small Parcel of Air," Part 4 of this report.

4. Schaefer, V.J., "The Production of Ice Crystals in a Cloud of Supercooled Water Droplets," Science, 104, 457 (1946).

5. Schaefer, V.J., "The Formation of Ice Crystals in Ordinary and Nuclei-Free Air," Ind. Eng. Chem., 44, 1300 (1952).

6. Langmuir, I., "The Growth of Particles in Smokes and Clouds and the Production of Snow from Supercooled Clouds," Proc. Am. Phil. Soc., 92, 167 (1948).

Part 4

THE MEASUREMENT OF HIGH CONCENTRATIONS OF ICE NUCLEI IN A SMALL PARCEL OF AIR

Vincent J. Schaefer

Among the problems associated with a study of atmospheric physics, such as the efficiency of dry-ice seeding or the use of silver iodide generators, is the determination of the number of active ice nuclei that may form because of variations in the techniques of forming the original nuclei.

Silver iodide aerosols[1] may be formed, for example, by reacting submicroscopic silver smoke with iodine vapor, by burning coke, charcoal, string, or paper covered with powdered silver iodide or impregnated with a solution of silver iodide prepared as a double salt with sodium iodide dissolved in acetone.

In addition to the preparation of submicroscopic smokes of pure silver iodide, some evidence has been found that indicates that the ability of this material to serve as an ice nucleus may be affected by traces of specific impurities, as well as by certain physical and chemical reactions. Alcohol vapor,[2] ultraviolet irradiation,[3] and traces of sulfur[4] are three examples of effects that may interfere with the effectiveness of silver iodide particles under specific conditions.

Various methods have been used[5] to evaluate these effects in a semiquantitative manner. A new quantitative method has been devised by the writer for determining the initial concentration of ice crystals in an aerosol sample and the subsequent behavior of those particles having a delayed reaction. The technique is simple and straightforward in its application to what is normally a tedious procedure.

EQUIPMENT USED FOR OBTAINING INITIAL ICE-CRYSTAL CONCENTRATION

Figure 1 illustrates the cold chamber and Fig. 2 the nebulizer used as a source of moisture to maintain a supercooled cloud in equilibrium with the chamber and the conditions of the experiment. At conditions of equilibria, a 4-cubic-foot home freezer lined with black velvet and having a working capacity of approximately 100 liters will warm up from -20° to about -14°C with moist air entering the chamber at the rate of about 18 liters per minute.

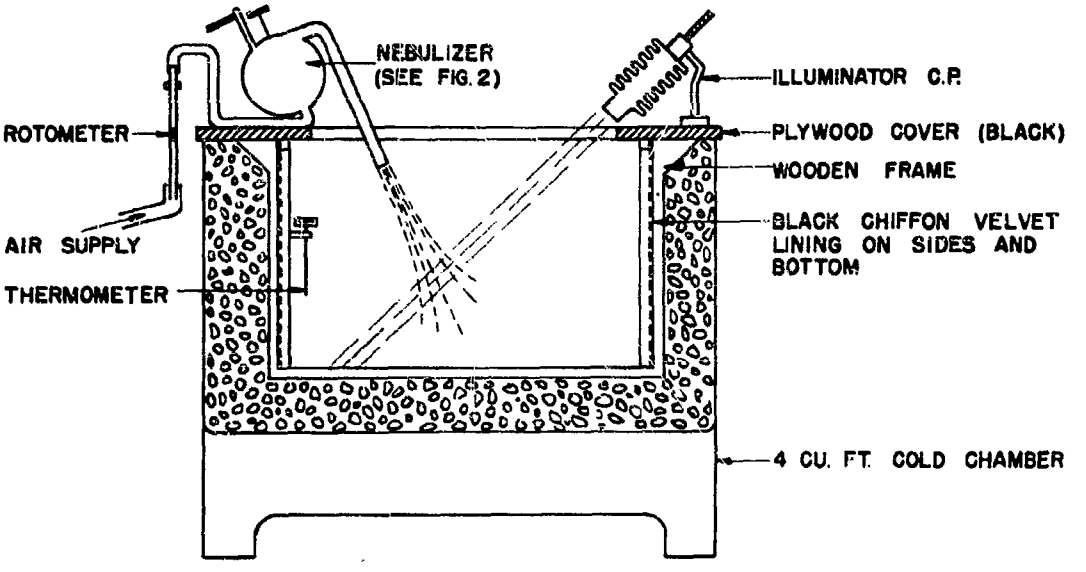


Fig. 1 Schematic diagram of cold chamber.

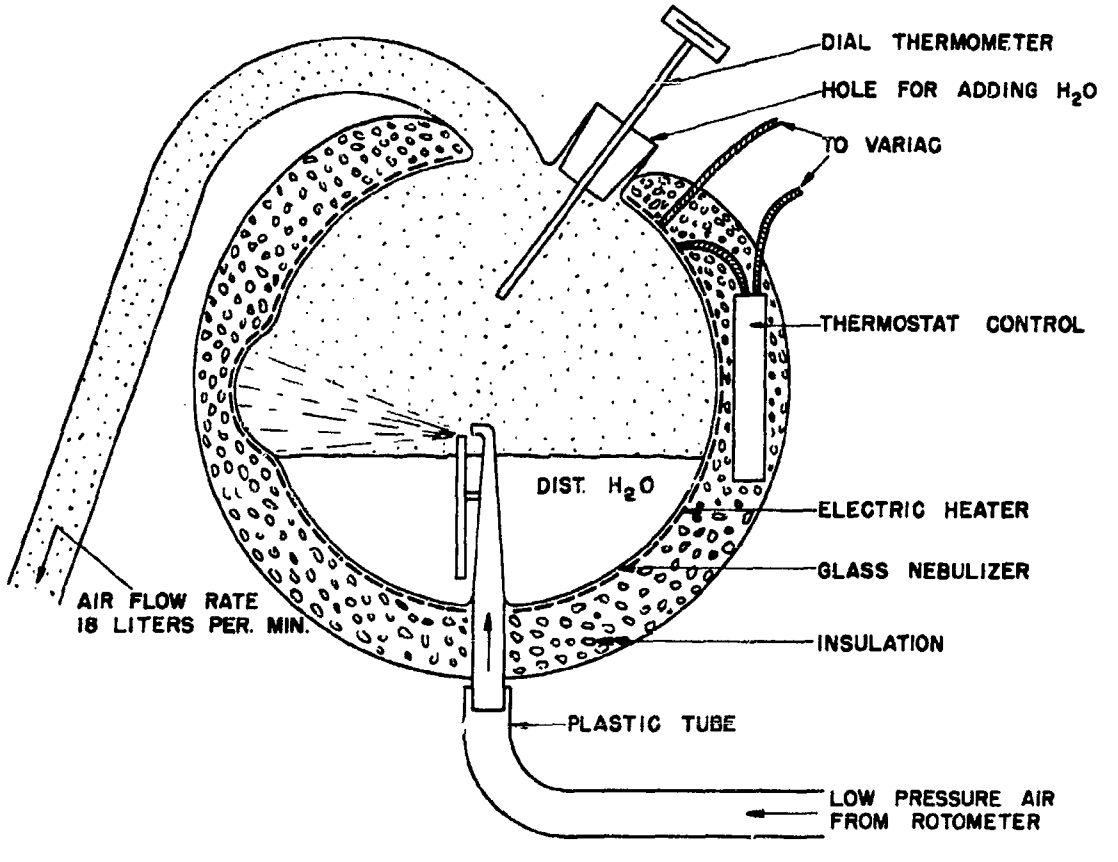


Fig. 2 Schematic diagram of continuous moisture supply apparatus.

A very important feature of the cold chamber is this black chiffon velvet lining. This is mounted on wooden frames that hold the cloth about 1-1/2 cm from the cold walls of the chamber. The velvet is porous enough to afford good heat interchange but tight enough to prevent fragmentation nuclei from passing into the chamber. When this arrangement is properly made, the velvet remains dry and frost-free. The most recent design of the cloth holder made by the writer utilizes a frame suspended from a plywood cover resting on top of the chamber. This eliminates all contact with the sides and bottom of the cold chamber.

The temperature of the water in the nebulizer is held at 14°C by use of a heating jacket whose temperature is controlled by a thermoswitch. About 130 grams of distilled water is used to fill the nebulizer. The liquid water content at equilibrium conditions approximates 1 g/m^3. Under ordinary operating conditions, sufficient condensation nuclei are included in the air supply and entrained from the surrounding air to maintain the particle size of the cloud droplets within the size range of 10 to 15 microns. Normally, the cloud forming in the chamber is entirely supercooled. Illumination of the chamber is effected by use of a microscope illuminator which produces a bright collimated beam having a cross-sectional diameter of 2.5 cm. In operation, this light beam is inclined at an angle of about 45° and is located within 10 cm of the outlet of the nebulizer, so that air having considerable turbulence can be observed shortly after emerging from the outlet tube of the nebulizer.

Before making observations, care must be taken to insure that all parts of the chamber and nebulizer are operating under conditions of equilibria. With the cold chamber running at maximum capacity, this condition will be realized within about 30 minutes. Once reached, it is possible to operate for six hours or more without doing more than restoring the level of the water supply of the nebulizer every two hours.

METHOD OF MAKING OBSERVATIONS

The procedure for making a typical experiment is as follows. With everything at equilibrium and the light beam disclosing a uniform cloud of supercooled water droplets, a piece of dry ice is held above the chamber and scratched with a knife edge so that eight or ten tiny grains of dry ice fall into the chamber and produce condensation trails of ice crystals. Within less than ten seconds the chamber is filled with a mass of twinkling ice crystals having an entirely different appearance from the supercooled cloud. At the instant that the seeding material is distributed throughout the chamber, a timer is actuated. At 30- or 60-second time intervals, the number of crystals in a unit volume is

roughly estimated. While this observation requires a fair degree of experience, it is feasible to make a rough approximation of the unit concentration by estimating the distance separating individual particles. Thus, if the particles are about 1 millimeter apart, the concentration is equivalent to 1000 crystals per cubic centimeter. After becoming familiar with the appearance of a cloud having about 1000 crystals per centimeter, it is feasible to estimate ten times as many, since this represents a separation of a little less than 1/2 millimeter. Similarly, if the distance between particles is about 2 millimeters, a value of 100 to 200 per cubic centimeter is indicated. The visual estimation method is aided by having an auxiliary illuminator having a parallel beam 1 mm by 10 mm. Such estimates become more accurate as the concentration decreases, so that by the time the concentration drops to 100 per cubic centimeter a fairly accurate estimate may be made.

When the concentration reaches this approximate value, a careful watch should be maintained for a new feature that appears. This is the first trace of a supercooled cloud. At a concentration of ice crystals between 50 to 70 crystals per cubic centimeter, coexistence of water droplets and ice crystals occurs. The crystals are growing at the maximum rate possible by the diffusion of water vapor and are beginning to have a falling velocity sufficiently great to permit a certain amount of growth due to interception of cloud droplets. Because of the more rapid rate of growth and the related increased falling velocity, the remaining crystals disappear from the chamber at a much faster rate than when the concentration is so high that the moisture is used up as fast as it enters the mass of ice crystals.

THREE TYPES OF TIME-CONCENTRATION CURVES

Figure 3 illustrates three types of decay rates observed when ice crystals are introduced into the cold chamber, using several methods for producing active nuclei.

Type A illustrates two cases where ice crystals were produced by methods that form them spontaneously. In these cases, the maximum concentration of ice crystals occurs immediately. This concentration falls off at a uniform rate dependent on the amount of moisture supplied to the crystals, which grow by diffusion of the water vapor to the crystals. When the concentration falls below 100 crystals per cubic centimeter, a new rate of disappearance by fall-out is introduced, since the remaining crystals are no longer forced to compete with one another for the moisture supply. At a concentration of about 70 crystals per cm^3, the crystals

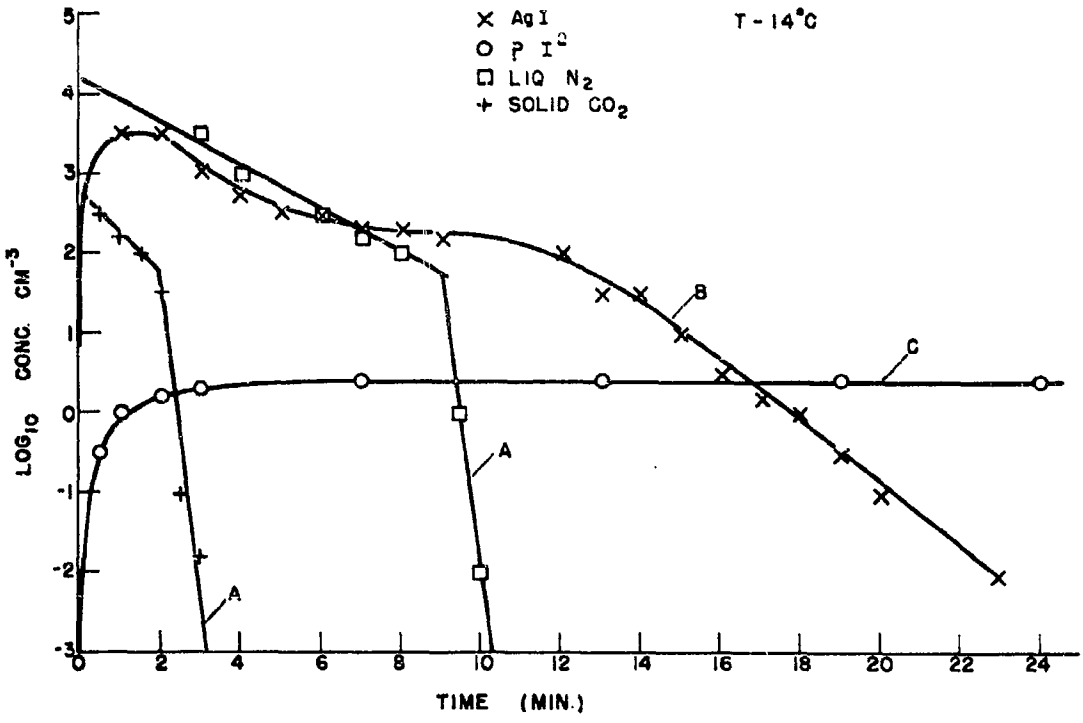


Fig. 3 Typical time-concentration curves.

coexist with supercooled droplets. Some coalescence with water droplets adds to the rate of growth of these remaining crystals to further increase their rate of disappearance by fall-out.

Type B is typified by the situation in which foreign particles serve as nuclei for ice-crystal formation. These may serve as sublimation and freezing nuclei or only as the former, depending upon the behavior of the particles when contacted by vapor or liquid water at temperatures below freezing. Since these particles are not initially ice crystals, a certain length of time is required for water molecules to deposit on the surfaces and form an ice-crystal surface. As originally pointed out by Vonnegut,(6) the rate of reaction of silver iodide for ice-crystal formation by sublimation is such that many nuclei in a specific air sample have a delayed reaction. This is nicely shown by Curve B in Fig. 3. Eventually, all particles above a critical size form crystals and settle out on the floor of the chamber.

The third effect illustrated in Fig. 3 is called Type C. In this case, a chemical reaction occurs within the chamber. Equilibria is reached slowly and is dependent on the rate of reaction and concentration of certain types of foreign particles in the air. A specific example, illustrated in Curve C of Fig. 3, is dependent on the chemical reaction between iodine vapor and submicroscropic metallic particles in the air of the laboratory. With iodine vapor alone, no ice crystals form.[7] In most air--particularly in air from laboratories where electric switches are used--the air contains many metallic particles; their concentration varies over a considerable range and from place to place. If a few small iodine crystals are kept in a chamber at a temperature of -14°C, the vapor pressure of the iodine is sufficient to cause an immediate reaction with certain of these aerosol particles to form iodides. Air containing submicroscopic silver and lead particles leads to the formation of many effective sublimation nuclei for ice-crystal formation. Provided the chamber is open to the surrounding air, a sufficient number of particles are carried into the chamber to cause a continual formation of new particles, so that the concentration curve remains at a fairly constant level. If outside air is excluded or the iodine crystals are removed, the effect disappears within a half hour or so.

It is, of course, possible to have several of these effects occurring simultaneously. This can lead to a complicated decay rate, which may be difficult to understand. For this reason, it is important to recognize the sensitivity of the iodine effect and guard against having free iodine in the air of the room or the chamber except when conducting research studies. In addition to coming from the evaporation of iodine crystals, reactive iodine may also be formed in the heat decomposition of various metallic iodides, from hydroiodic acid, and from iodoform.

UTILIZATION OF THE TIME-CONCENTRATION OBSERVATIONS

In using the technique described in this paper, only that illustrated as the A-type curve may be used effectively to indicate the initial value of crystal concentration by extrapolating the initial portion of the straight-line rate-of-decay curve back to zero time. When this is done for the curves presented in Fig. 3, values of 2.75×10^7 and 4.2×10^9 particles are indicated to have been generated by the seeding operations used. These values are obtained by multiplying the number of crystals per cubic centimeter by the volume capacity of the cold chamber. It should be realized that this value is probably a conservative figure. Coagulation, evaporation, fall-out, and melting may tend to reduce the initial concentration before equilibrium conditions are reached. Since the slope of the curve and the length of time which transpires before coexistence with supercooled cloud

droplets occurs are both determined by the concentration of actual crystals, the method holds promise of serving as a useful tool for obtaining the actual number of crystals produced spontaneously.

The initial concentration of silver iodide particles may be estimated by considering the region under Curve B and assuming an average falling velocity of the particles during the total period of activity. A more effective use of the method in this case would be to adopt a uniform sampling procedure, followed by establishment of the slope of the time-concentration curve under conditions in which the moisture supply and temperature of the chamber are held constant. A comparison of such curves would provide an easy method for evaluating various methods of preparation or modification of aerosol samples of ice-crystal nuclei.

Lack of time prevented the application of this simple technique to a thorough study of the behavior of the metallic iodides as ice nuclei. There are so many variations and changes possible in making such aerosols, and satisfactory results are of such potential importance, that a careful study along such lines would constitute an important scientific contribution to the advance of experimental meteorology and atmospheric physics.

REFERENCES

1. Vonnegut, B., "Techniques for Generating Silver Iodide Smokes," J. Colloid Sci., 5, 37 (1950).

2. Vonnegut, B., "Influence of Butyl Alcohol on Shape of Snow Crystals Formed in the Laboratory," Science, 107, 621 (1948).

3. Reynolds, S.E., Vonnegut, B., et al., "Effect of Sunlight on the Action of Silver Iodide Particles as Sublimation Nuclei," Bull. Am. Meteor. Soc., 32, 47 (1951).

4. Vonnegut, B., and Neubauer, R., "Recent Experiments on the Effect of Ultraviolet Light on Silver Iodide Nuclei," Bull. Am. Meteor. Soc., 32, 356 (1951).

5. Schaefer, V.J., "The Production of Clouds Containing Supercooled Water Droplets or Ice Crystals Under Laboratory Conditions," Bull. Am. Meteor. Soc., 29, 175 (1948)

6. Vonnegut, B., "Nucleation of Supercooled Water Clouds by Silver Iodide Smokes," Chem. Rev., 44, 277 (1949).

7. Vonnegut, B., "The Nucleation of Ice Formation by Silver Iodide," J. Applied Phys., 18, 593 (1947).

Part 5

SILVER AND LEAD IODIDES AS ICE-CRYSTAL NUCLEI

Vincent J. Schaefer

The effectiveness of silver iodide as an ice-crystal nucleus first discovered by Vonnegut[1] has had far-reaching consequences in the field of experimental meteorology. A search for other substances that might be even more effective has been continued by various workers in the field. A survey by the writer[2] related to some of the probable natural ice nuclei showed that soils of volcanic origin and clays from glacial deposits served as active ice-crystal nuclei in the temperature range of -12° to -22°C. Thus far, no naturally occurring nuclei have been discovered that work in the range of 0° to -5°C, although there is reason to believe[3] that frazil ice may be initiated by freezing nuclei active in this temperature range. No serious attempt has been made by the writer to investigate this important relationship, but it is hoped that this will be possible before long.

When Vonnegut was searching the x-ray crystallographic data for crystals having a lattice arrangement similar to ice, he found that silver iodide and lead iodide should be nearly ideal. Along the a-axis, lead iodide matched the ice dimension even better than silver iodide. Despite this fact, Vonnegut concentrated his efforts toward a study of silver iodide, since this substance had a much lower solubility in water and closely matched the ice structure along both the a-axis and c-axis.

By using the continuous cloud chamber[4] a comparison has been made between silver and lead iodide. Submicroscopic smoke particles of each of these substances were made by two different methods. Figure 1 illustrates a cross section of the chamber used. In the first, a Tesla coil was connected to a spark gap made of pure silver or pure lead electrodes. These were placed in a clean glass container containing a few small crystals of iodine held at room temperature. When a spark discharge occurred, submicroscopic metallic particles were produced which reacted with the surrounding free iodine vapor to form particles of the iodide. Samples of the air containing this invisible smoke could then be introduced into the closed cloud chamber under easily controlled conditions.

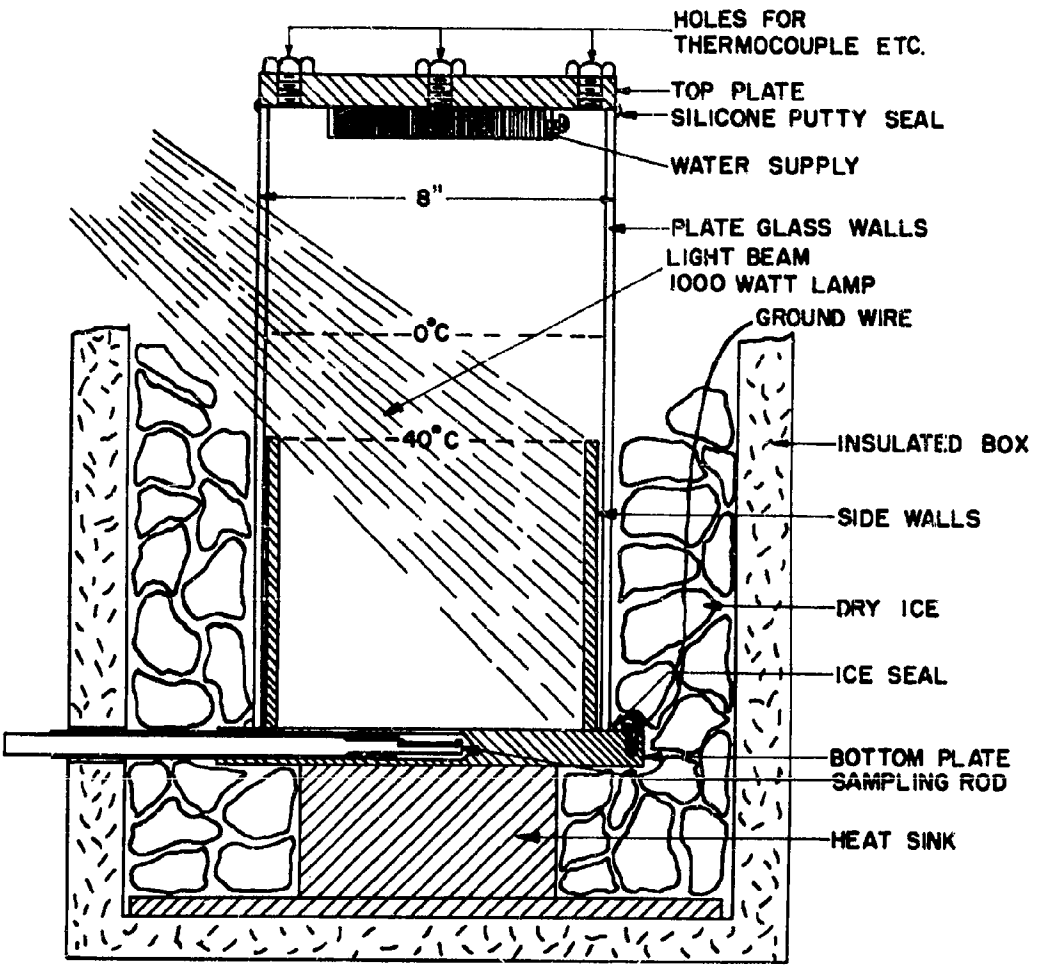


Fig. 1 Continuous cloud chamber for studying performance of nuclei under controlled conditions.

The second method utilized a heated platinum filament coated with a thin layer of powdered lead iodide or silver iodide. By heating the filament, small particles of these iodides vaporized to form a faintly visible bluish aerosol.

METHOD OF COMPARING SILVER AND LEAD IODIDES AS ICE NUCLEI

Using a suitable valve system, samples having a volume of a few cubic millimeters were introduced into the continuous cloud chamber. Figure 2 illustrates the temperature distribution in the chamber. This

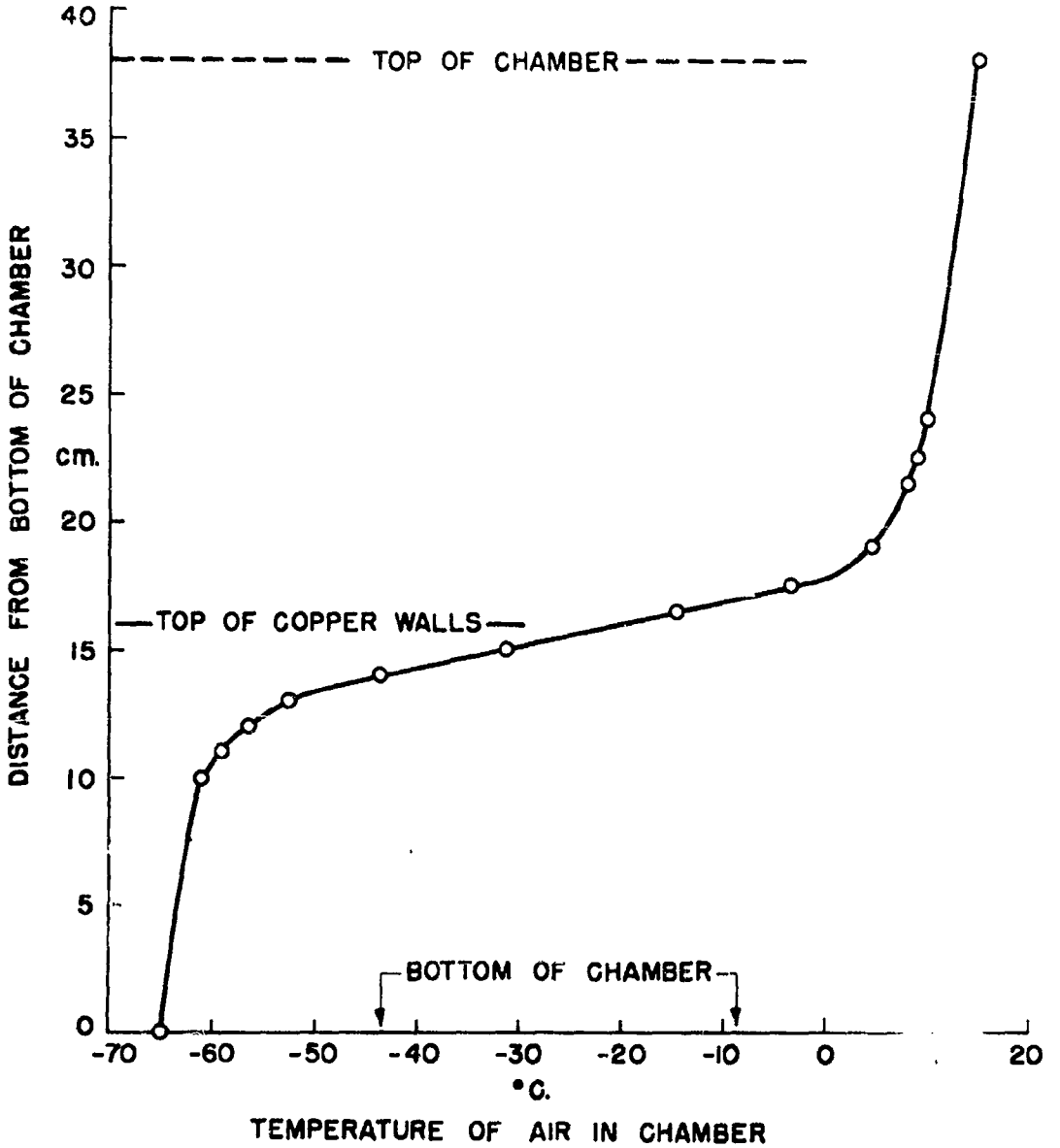


Fig. 2 Temperature profile in continuous cloud chamber.

was operated under two conditions of absolute humidity, viz., (1) supersaturation with respect to ice at -5°C and (2) supersaturation with respect to water at +5°C. The samples were introduced at two levels in the chamber, one having a temperature of +5°C and the other about -5°C. Two inlets were used for introducing aerosol samples. In this manner, simultaneous comparisons could be made between two different materials.

Aerosol samples of silver iodide and lead iodide were prepared by the methods described previously. No appreciable differences were observed in the formation and growth of ice crystals on nuclei produced by these two different techniques. There should be considerable differences in crystal structure, since in one case the particle consists of an adsorbed layer of iodine on a metallic particle, while in the other case it probably consists of a homogeneous crystal of the metallic iodide.

THE ROLE OF SILVER AND LEAD IODIDE PARTICLES AS SUBLIMATION NUCLEI

The first series of experiments was made under conditions in which the submicroscopic smokes were introduced into the -5°C region with the air supersaturated with respect to ice. Under these conditions, the tiny particles could serve as sublimation nuclei for ice-crystal formation if they possessed a suitable structure for such a role. Samples of silver iodide and lead iodide smokes were introduced side by side in order to make direct comparisons.

It was found that both silver iodide and lead iodide served with equal effectiveness as sublimation nuclei at temperatures colder than about -5°C.

THE ROLE OF SILVER AND LEAD IODIDE PARTICLES AS FREEZING NUCLEI

A different relationship exists, however, when these two kinds of particles are compared as freezing nuclei. To do this, it is necessary to introduce aerosol samples at the +5°C level under conditions of supersaturation with respect to water. In order to do this, it is necessary to permit all foreign nuclei to "rain out." The particles thus serve as condensation nuclei and form cloud droplets in the warm zone of the chamber. If a direct comparison is made between silver iodide and lead iodide under these conditions, both substances seem to work equally well as condensation nuclei. As they fall into the cold zone of the chamber, each water droplet that formed on a silver iodide particle is observed to shift to an ice crystal at about -5°C.(5)

The droplets formed on lead iodide particles behave differently, however. After serving as nuclei for water-drop formation at +5°C, they fall into progressively colder air, supercool, and do not cause ice-crystal formation until cooling to about -20°C.

This difference between the effectiveness of silver iodide and lead iodide in their role as freezing nuclei may be related to the difference in solubilities of these two substances. At 0°C, the solubility of PbI_2 is 4×10^{-2}g/100 ml of water, and that of AgI is about 3×10^{-7}g/100 ml. This difference in solubility of more than 100,000 times may account for the observed differences.

STUDIES OF PARTICLES UNDER THE MICROSCOPE

After noting the relationships between lead and silver iodide, a different type of experiment was devised. A microscope was placed in a cold chamber and cooled to the surrounding temperature of about -20°C. Large lead iodide crystals were made by dissolving 4 grams of powdered lead iodide in a liter of boiling distilled water. Upon cooling, many very beautiful, extremely thin hexagonal crystals precipitated out of solution. Many of these crystals were so thin as to produce brilliant interference colors. Under the microscope they appear as extremely flat and featureless hexagonal plates, as shown in Fig. 3. Many of these crystals gather on the surface of the water as a monolayer and appear to be hydrophobic. By lowering a clean microscope slide through the water surface, a sheet of these crystals may be easily transferred to its surface.

Suitable objective and ocular lenses were put in the microscope to give a magnification of 100X. Under such conditions, 20-micron droplets are easily observed as they land on the surface of a slide, since they appear to be about 2 mm in diameter. Ice crystals produced in a supercooled cloud in the chamber by dry-ice seeding appear to be from 5 to 15 mm in diameter under the same conditions. By this method, it is quite easy to observe the effect of different types of surfaces on supercooled water droplets.

When supercooled water droplets land on a dry surface of the glass microscope slide, they immediately evaporate. If the surface is coated with a thin layer of ice, they freeze immediately. If ice crystals land on the clean glass surface, they remain unaffected by the heat of the microscope illuminator and persist indefinitely. A supercooled water droplet landing on one of these crystals immediately freezes.

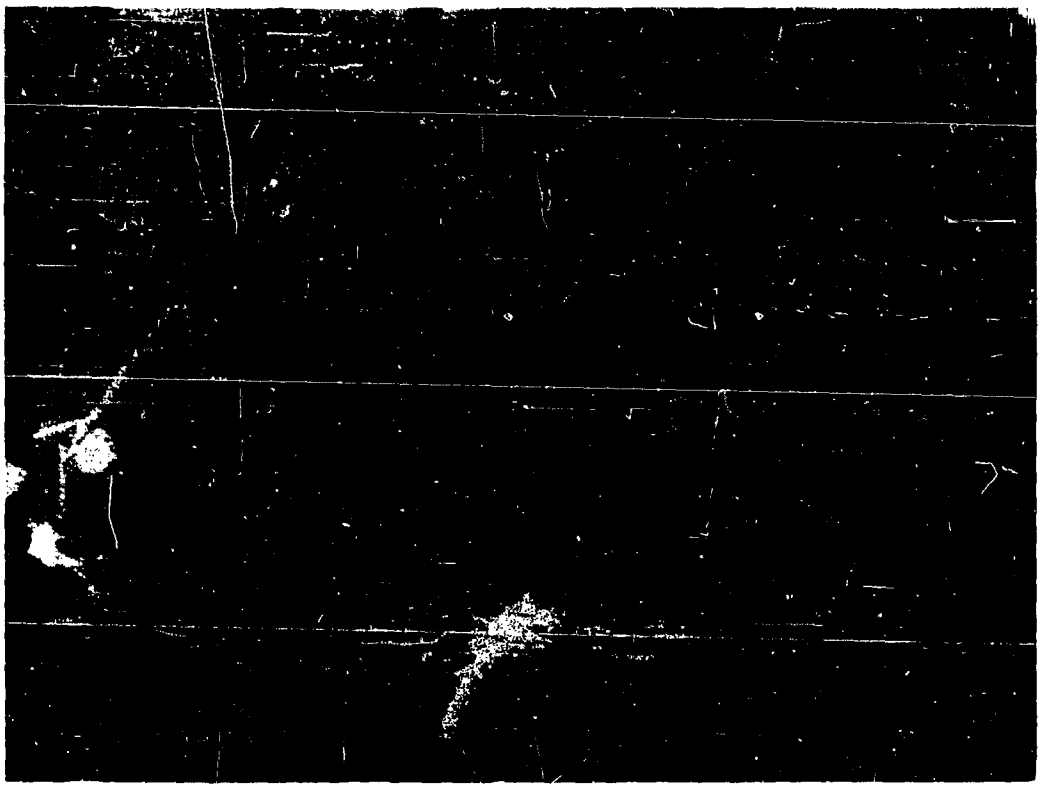


Fig. 3 Lead iodide crystals in cooling water.

Under such conditions, it is of interest to observe the effect of lead iodide and silver iodide crystals upon supercooled water droplets that contact their surfaces. An aggregation of lead iodide and silver iodide crystals was placed on a clean glass surface so that comparisons could be made within the viewing field of supercooled droplets landing on (1) dry glass, (2) ice crystals, (3) silver iodide, and (4) lead iodide.

Under these conditions, the droplets evaporated after landing upon the dry glass and the flat surfaces of the lead iodide crystals. They froze instantly on the ice crystals and the silver iodide particles. These latter crystals were not so symmetrically formed as those of the lead iodide.

The differences observed in the freezing of the droplets were consistent with the theory that silver iodide is a good freezing nucleus but lead iodide is not.

A POSSIBLE REASON FOR THE ANOMALOUS BEHAVIOR OF LARGE LEAD IODIDE CRYSTALS

A possible explanation of the anomalous behavior whereby a supercooled droplet evaporates before freezing while resting on the surface of large lead iodide crystals has been proposed by David Turnbull of this laboratory. He points out(6) that the extreme thinness of the lead iodide crystals (which often show first-order interference colors) suggests that their thickness is a direct function of the effective size of the nuclei upon which they form, and that the flat surface which develops in the direction of the a-axis represents an area free of edges, owing to the termination of screw dislocations in the hexagonal plane of the crystal. These edges are necessary to inaugurate further crystal growth either of the same material or of a closely related structural molecule due to epitaxy. If such sites are not available, further growth is inhibited. Since this is the portion of the lead iodide crystal whose dimensions are nearly identical to those of water, this hypothesis may suggest the reason why lead iodide is suitable as a sublimation nucleus but not as a freezing nucleus. The only suitable sites for growth would thus be at the edge of the hexagonal plates. Bulk water contacting such regions would tend to dissolve the active surface. Vapor water would form an ice crystal directly from the gaseous phase and thus could not cause solution. Water droplets landing on the flat surfaces of the crystals evaporate before freezing because of the absence of nucleating sites on this part of the crystal. Presumably they would freeze or at least leave an icy residue nearby if nucleating sites were available, since both ice crystals and silver iodide under the same conditions are effective in this respect.

Time did not permit carrying out a critical experiment of this nature. A large lead iodide crystal should be mounted on a slide, checked for behavior with respect to liquid and gaseous water vapor, and then deformed by heat or pressure. Following deformation, the surface along the a-axis might be expected to serve as a good site for ice-crystal formation from the gaseous phase. It might also serve to initiate crystallization of water droplets that would be small compared with the dimensions of the lead iodide crystal.

NEED FOR FURTHER STUDIES IN THIS FIELD

These interesting relationships between ice crystals, lead iodide, and silver iodide emphasize the importance of further research along the lines described in this paper.

There are many methods that may be used to produce these metallic iodides as submicroscopic particles. They may be vaporized directly by heating the dry powder in a flame or on a hot surface. Solutions may be atomized directly to form a hydrosol or sprayed into a burning flame to be vaporized. Iodine vapor may be passed over silver or lead electrodes. Burnable material such as paper, string, charcoal, or coke may be impregnated with the iodide as powder or with solutions of these materials, then burned and the vapor condensed. The effectiveness as an ice nucleus of aerosols produced by these various methods may then depend on the manner in which the individual particles form or crystallize and on subsequent reactions that may occur in the atmosphere as gases adsorb on them, ultraviolet light shines on them or they in turn become part of a synergistic reaction. Many of these effects may be studied in the laboratory under controlled conditions. Most of them should be tested in the free atmosphere.

REFERENCES

1. Vonnegut, B., "The Nucleation of Ice Formation by Silver Iodide," J. Applied Phys., 18, 593 (1947).

2. Schaefer, V. J., "The Formation of Ice Crystals in the Laboratory and the Atmosphere," Chem. Rev., 44, 291 (1949).

3. Schaefer, V. J., "The Formation of Frazil and Anchor Ice in Cold Water," Trans. Am. Geophys. Union, 31, 885 (1950).

4. Schaefer, V.J., "Continuous Cloud Chamber for Studying Small Particles in the Atmosphere," Ind. Eng. Chem., 44, 1381 (1952).

5. Schaefer, V. J., "Formation of Ice Crystals in Ordinary and Nuclei Free Air," Ind. Eng. Chem., 44, 1300 (1952).

6. Turnbull, D., private communication.

Part 6

AN OBJECTIVE 30-DAY FORECAST METHOD FOR PRECIPITATION AND TEMPERATURE AT ALBANY, NEW YORK, USING HIGH-PRESSURE-CENTER LOCATIONS OVER NORTH AMERICA

Raymond E. Falconer and Kiah Maynard

During June 1951, Lt. W.E. Hubert and Chief H.J. Wells, Navy personnel then assigned to Project Cirrus at the G-E Research Laboratory in Schenectady, were working on data concerning sublimation nuclei counts which were being taken on a routine basis by personnel of the Mt. Washington Observatory on Mt. Washington, New Hampshire. One interesting fact discovered by Chief Wells was that the nuclei count--whether light, moderate, or heavy--on the summit of Mt. Washington bore a very good relation to the current position of major high-pressure cells over the United States and Canada. By predicting the expected position of the high-pressure cells 24 hours in advance, he was able to make a rather good forecast of whether the nuclei count on Mt. Washington would be light, moderate, or heavy. Apparently, the air trajectories from regions rich or deficient in ice nuclei were controlled by these situations.

This suggested to the senior author of this report that there might be some relation between the position of the major high- and low-pressure cells and subsequent rainfall occurring one, two, or any number of days later over a given area. With the able assistance of the co-author, Kiah Maynard,(1) who contributed a number of ideas and considerable effort in working over the data, a long-range forecasting system has been developed which appears to have interesting possibilities.

Our first work on this forecast system was begun in June 1951 and has continued intermittently as time permitted during the past three summers. Initially, only one- and two-day forecasts were attempted, and the positions of both the prominent high- and low-pressure areas were used. After forecasts had been made for about 50 days, we decided to see whether it would be better to consider only the low-pressure centers, only the high-pressure centers, the nearest high or the nearest low to Albany, or the combination of all the highs and lows, in determining a forecast. It was found that a better score could be made by using all the highs only, and since that time high-pressure centers have been used exclusively.

Preceding Page Blank

The same technique is used to make a forecast for precipitation or temperature departure from normal any number of days in advance of a given day. The description of the forecasting method that follows concerns the 30-day forecast, because we have found that for some reason this has shown consistently greater accuracy than the one-, five-, six-, seven-, or fourteen-day forecasts which have also been tried. For instance, for the period from April 2 to the end of August 1953, the following accuracies were obtained: one-day, 62 per cent; five-day, 57 per cent; six-day, 66 per cent; seven-day, 64 per cent; fourteen-day, 58 per cent; and thirty-day, 79 per cent.

It was found that the most convenient daily map available at this office from which surface high- and low-pressure centers can be located is the small 1:30 p.m. map of North America included on the Daily Weather Map issued from Washington, D.C. Pressure centers were located on this map by using a transparent overlay grid on which the 5° lines of latitude and longitude were drawn. Various arrangements of letters and numbers to identify either the 5° squares of latitude and longitude or the intersection of the 5° lines of latitude and longitude have been used. In general, we have chosen letters to represent lines of latitude and numbers for the lines of longitude.

In our first work, the pressure centers were determined by putting the grid overlay onto the map and noting which square bounded by adjacent 5° latitude and longitude lines best described the pressure-center location. Because pressure centers are often spread over a much larger area than these 5° squares, it was later decided to use a slightly different system.

A new grid was made (see Fig. 1) on which the letters and numbers refer to the intersections of the 5° latitude and longitude lines. Significant highs were then located by fitting the pressure center into a square having 10° of latitude or longitude on a side, and then using the letter-number designation for the latitude-and-longitude intersection at the center of this 10° square. While there may actually be little difference in the two methods, we have felt that the latter one is a little better, and it is the one we have been using for the past two years.

In determining pressure-cell locations, we have used only those which have at least one but preferably two or more closed isobars around the center. If a high-pressure cell is centered well up in Canada with a long ridge extending well down into the United States, it has been felt that the southern crest of this ridge could be regarded as a center. A large high-pressure ridge with two centers some distance apart is

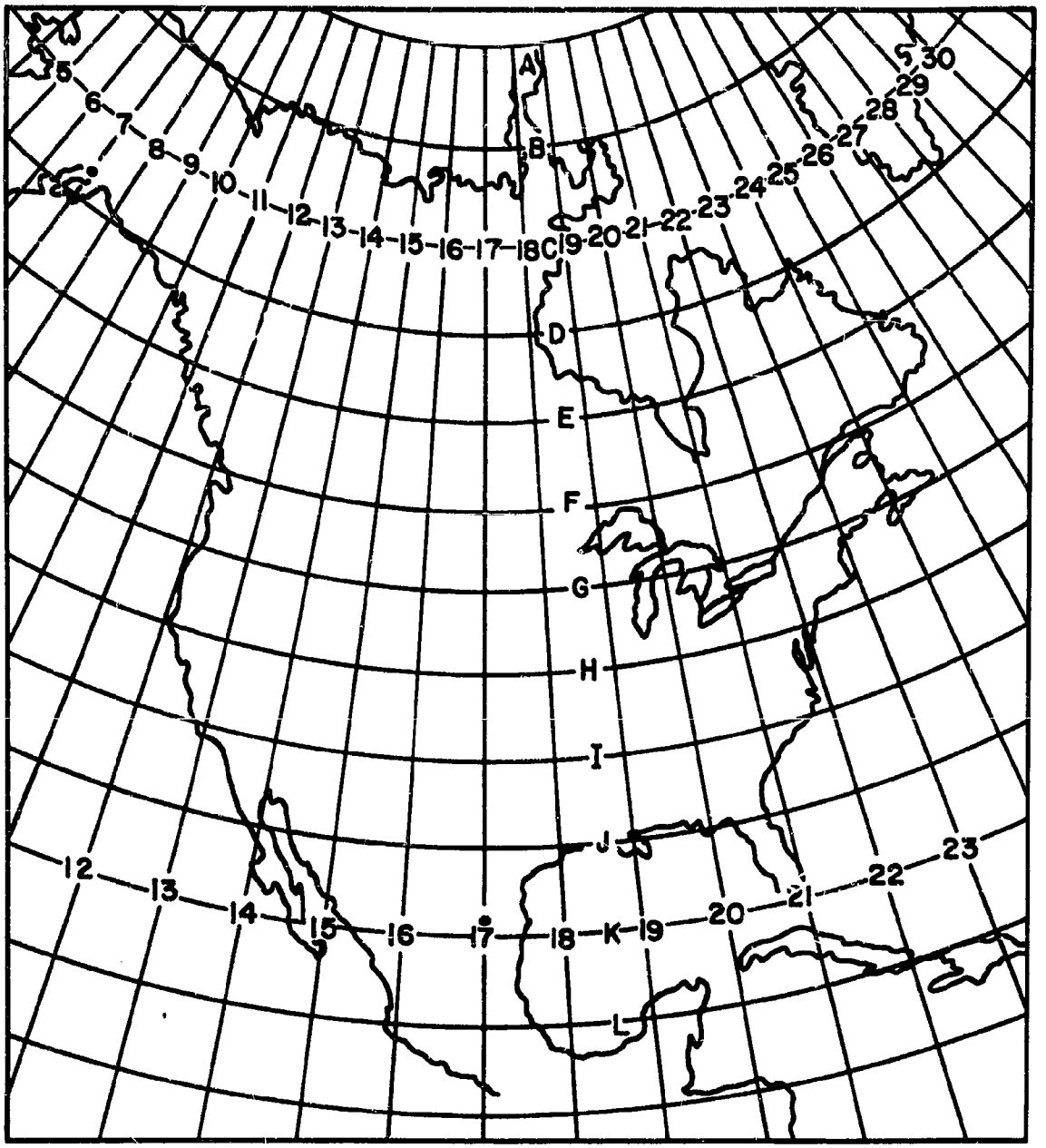


Fig. 1 Overlay grid for identifying pressure-center locations.

considered as two separate centers. If it is difficult to determine which of two adiacent 10° squares best describes the position of the center, the one nearest to Albany, New York, has been used. There is some occasional difficulty in determining the actual center of cells such as the Atlantic and Pacific semipermanent highs because they are often on the edge or just off the edge of a particular map. A northern hemisphere map would remedy this situation, of course, but our treatment of such situations by considering when necessary the crest of high-pressure ridges that protrude onto the edge of the map as centers has worked reasonably well.

In assembling data for constructing the master grid, the following method is used. The pressure-center locations for each day are entered on a monthly data sheet similar to that shown in Table I. The amount of precipitation recorded as falling at Albany 30 days later, during a 24-hour period (1:30 a. m. to 1:30 a. m.), is entered after the pressure data of the appropriate date. Precipitation amounts for the 24-hour period from 1:30 a. m. to 1:30 a. m. are obtained from the small precipitation map also found on the Daily Weather Map. Several months of this type of data (i. e., pressure centers related to rainfall 30 days later) are used in making up the final table from which forecasts are made. (Although precipitation recorded at the Albany airport was used in making up the master forecast chart, we have taken the liberty of stating that this is a forecast for the Albany-Schenectady area, since we realize the difficulty in forecasting for just one rain gage.)

The next step is to construct another table showing the number of times rain and no rain occurred at Albany 30 days after a high-pressure center has been located at the various 5° intersections of latitude and longitude. Such a table is shown in Table II. In this table, the letters across the top refer to the 5° latitude lines and the numbers in the left-hand column refer to the longitude lines as shown in Fig. 1. The columns under each letter are divided into two--one for entering the occurrences of rain and the other for no rain. The number in the center of the rain column indicates the total number of times that rain has occurred 30 days after a high-pressure center has been located at that particular intersection. The figure to the upper left of this same entry shows the number of times that the amount of rain has been between a trace and 0. 10 inch; the number in the lower left shows the number of rains between 0. 10 and 0. 30 inch; the lower right number refers to rains between 0. 30 and 1. 50 inches; and the number to the upper right refers to the rains of over 1. 50 inches.

Table II is actually the summation of data compiled for each of the years 1950, 1951, and 1952 during the months of April through August--about 459 days in all. This is the table from which a forecast

TABLE I

Daily Position of Significant High-Pressure Cells During May 1952, and 24-Hour Amounts of Rainfall--1:30 a. m. to 1:30 a. m. -- Recorded at Albany, 30 Days Later*

Date	A	B	C	D	E	F	G	H	I	J	K	L	Albany 24-Hour Precipitation on Date Indicated	Albany Precipitation 30 Days Later
May 1, 1952		17	22 30							20			- .00	- .00
2		23						17 11		23			- .00	- 3.45
3	7	29				18		20	18 11				- .00	- .00
4				14			11		20	18			.00	.00
5			17			13		22		18			.00	.10
6							18 10				21		- .04	- .00
7		17			21 14	15	20		15		20		- .00	- .05
8			21 17				19	12			23		- .00	- .00
9			22	17 11						12	23		- .00	- .00
10		25 6				16	16				12		- .12	- .04
11		29	12		18					18			.59	T
12	18		12		26	13 18					18		- .96	- T
13	19		29						19	19			.05	.00
14		20 14						11		21			- T	- .00
15		30	20	10						20 23			- .18	- T
16				8 16		25			11	24			- .00	- .01
17				16		17		23		23			.12	.00
18							18 20	11					- .09	- .47
19		10				20 27		23 16	10	23			- .00	- .00
20						23 19		25			18		- .27	- .09
21				18	26			11	20		23		.22	.00
22				22	28		10	21					.00	T
23			17		26		21 10			23			- .00	- .03
24				23			10	23					.01	.00
25		26		26		10		24	17				.68	.01
26	15					27		20					T	.00
27						15			21 10				- .00	- T
28			30 22				17		22				- .00	- .00
29		21		26				19	24				.33	.00
30					28		22	25					.00	.28
31		23				17					19		.03	.00

*Letters at top of table refer to 5° lines of latitude, and numbers in body of table refer to lines of longitude according to grid shown in Fig. 1. Pressure centers are determined from small 1:30 p. m. surface map of North America included on the Daily Weather Map issued by the U. S. Weather Bureau from Washington, D. C.

can be made. While several more years of data might be included, lack of time has prevented us from doing this. Presumably, more data would make some areas even stronger for rain or no rain, while others would show about as many cases of each.

To make a forecast requires only two or three minutes, once the summary shown in Table II has been made. When the Daily Weather Map arrives from Washington (usually a day or two late at Schenectady), the overlay grid (see Fig. 2) is placed on the small 1:30 p.m. surface map of North America and the position of the prominent high-pressure centers for that day are determined. We then find in Table II the number of occurrences of rain and no rain for each of the centers thus located.

A small table is then made (see Table III) listing each pressure-center location followed by the number of times it has rained or has not rained. Rather than use both the number of rain cases and no-rain cases in computing the forecast, we use a number that is the excess of one over the other. That is, if there are more times that it has rained than not rained, the number of no-rain cases is subtracted from the number of rain cases and the resulting number is used in the final computation. A plus sign is put in front of this number to indicate an excess of rain occurrences. If there are more no-rain cases, the same thing is done, but the number representing the excess of no-rain cases is preceded by a minus sign.

The values thus obtained for each pressure center are simply added together algebraically, and if the result is a positive number a forecast for rain is called for. If the result is a negative number, of course a no-rain forecast would be indicated.

To obtain a forecast for the amount of precipitation to be expected, we enter in the appropriate columns shown in Table III the number of times that the rainfall was light, moderate, heavy, or very heavy for each pressure-center location as found in Table II. If rain is forecast, then these columns are added. If the total in the moderate or heavy rain column is equal to one half or more of the total in the light rain column, then either moderate or heavy rain is forecast, depending upon which of the two is greater. The value of one half is not necessarily the correct one to use, but as a first approximation gives fairly good results. It might be better to use a more definite ratio obtained from the actual number of light, moderate, heavy, and very heavy rain occurrences during the period covered by Table II.

TABLE II

Master 30-Day Forecast Chart for Rain or No Rain
In the Albany-Schenectady Area During the Period May Through September*

	A		B		C		D		E		F		G		H		I		J		K	
	Rain	No Rain	Rain	No Rain	Rain	No Rain	Rain	No Rain	Rain	No Rain	Rain	No Rain	Rain	No Rain	Rain	No Rain	Rain	No Rain	Rain	No Rain	Rain	No Rain
1																						
2																						
3																						
4		1					1_{1}															
5					1_{1}		$^{1}1$															
6			$^{2}_{1}3$	1	1	2	1^{1}															
7							$_{2}^{2}2$		$_{1}^{1}1$		1_{1}	2										
8			$_{1}^{1}1$	1		1	$^{1}1$	1	$^{2}_{1}3$		$^{7}8_{1}$	12	$^{3}5_{2}$	9	$^{2}2$	3		1				
9	1_{1}	3		5	$^{1}1$	3		1	1	3	$^{8}_{1}10_{3}$	7	$^{7}_{5}15_{3}$	20	$^{6}_{3}13^{1}_{3}$	21	$^{6}_{3}10_{1}$	5	$^{1}1$	2		
10		1	1_{1}	1		2	$^{1}1$			1	$^{3}_{1}5^{1}$	4	$^{7}_{3}13_{3}$	14	$^{11}_{2}17_{4}$	26	$^{10}_{8}35^{1}_{7}$	24	$^{4}_{1}6_{1}$	8		
11	$^{1}1$	1	$^{4}_{2}7_{1}$	7	$^{4}5_{1}$	2		2		2	$_{2}^{2}2$	1	$^{3}_{1}4$	3	$_{2}^{4}4^{1}_{1}$	7	$^{4}_{1}8_{3}$	6	$^{6}_{1}9_{2}$	12	$^{1}1$	1
12			$^{8}_{1}12_{6}$	11	$^{7}9_{2}$	4		1		3	1_{1}	1	$^{2}2$			1	$^{1}1$		1_{1}	3	$^{4}_{1}7_{2}$	2
13	$^{2}2$	2	$_{1}^{2}2_{1}$	4	$^{2}2$	1		1	$^{1}_{1}2_{1}$	2	$^{1}_{3}6_{2}$	4	$^{1}1$									
14	$^{2}_{1}3$	4	$^{1}_{1}2_{1}$	5	$^{1}1$		$^{1}1$	2	$^{2}2$	6	$^{3}_{1}5_{1}$	2	$^{1}_{1}3_{1}$	5	$^{2}_{1}3$	2	$^{1}1$					
15	$^{1}_{1}2$	4	$^{2}_{2}6_{2}$	6	$^{1}_{2}3$	3	$^{1}1$	5	$^{2}3^{1}$		$^{9}_{3}14^{1}_{1}$	7	$^{1}_{1}3_{1}$	4	$^{1}_{2}4_{1}$	3	$^{6}6$	2		1		
16	$^{1}_{3}4$	5	$^{2}_{1}4_{1}$	5	$^{1}_{1}2$	4	$^{4}4$	8	$^{2}_{1}3$	3	$^{3}_{4}7$	2	$^{3}_{2}6_{1}$	4	$^{3}3$	5	$^{2}2$	1				
17		4	$^{6}_{1}7$	4	$^{1}_{3}4$	3	$^{2}6^{1}_{3}$	11	$^{1}_{2}6^{1}_{2}$	4	$^{4}5_{1}$	15	$^{4}6_{2}$	8	$^{2}_{1}4^{1}$	9	$^{3}4_{1}$	1				
18	$^{1}1$	2	$^{1}_{1}2_{1}$	2	1_{1}	4	$^{4}6$	4	$^{1}1$		$^{1}1$	7	$^{5}_{3}9_{1}$	8	$^{4}_{1}7_{2}$	11	$^{4}_{1}5$	5	$^{5}_{1}6$	5	$^{4}5_{1}$	5
19	$^{1}1$	2		2	2_{2}	2		1	$^{6}7_{1}$	1	$^{4}_{1}5$	6	$^{4}7_{3}$	9	$^{6}_{2}8$	9	$^{2}_{1}5_{2}$	7	$^{9}_{1}11_{1}$	15	$^{4}_{2}8_{2}$	6

12			$^{3}_{1}12_{6}$	11	$^{7}9_{2}$	4		1		3	1_{1}		$^{3}2$			1	$^{1}1$		1_{1}	3	$^{4}_{1}7_{2}$	2
13	$^{3}2$	2	$_{1}2_{1}$	4	$^{2}2$	1		1	$^{1}_{1}2$	2	$^{1}_{3}6_{2}$	4	$^{1}1$									
14	$^{3}_{1}3$	4	$^{1}_{1}2$	5	$^{1}1$		$^{1}1$	2	$^{2}2$	6	$^{3}_{1}5_{1}$	2	$^{1}_{1}3_{1}$	5	$^{2}_{1}3$	2	$^{1}1$					
15	$^{1}_{1}2$	4	$^{2}_{2}6_{2}$	6	$^{1}_{2}3$	3	$^{1}1$	5	$^{2}3^{1}$		$^{9}_{3}14^{1}_{1}$	7	$^{1}_{1}3_{1}$	4	$^{1}_{2}4_{1}$	3	$^{6}6$	2		1		
16	$^{1}_{3}4$	5	$^{2}_{1}4_{1}$	5	$^{1}_{1}2$	4	$^{4}4$	8	$^{2}_{1}3$	3	$^{3}_{4}7$	2	$^{3}_{2}6_{1}$	4	$^{3}3$	5	$^{2}2$	1				
17		4	$^{5}_{1}7$	4	$^{1}_{3}4$	3	$^{2}6^{1}_{3}$	11	$^{1}_{2}6^{1}_{2}$	4	$^{4}5_{1}$	15	$^{4}6_{2}$	8	$^{2}_{1}4^{1}$	9	$^{3}4_{1}$	1				
18	$^{1}1$	2	$^{1}_{1}2_{1}$	2	1_{1}	4	$^{4}6$	4	$^{1}1$		$^{1}1$	7	$^{5}_{3}9_{1}$	8	$^{4}_{1}7_{2}$	11	$^{4}_{1}5$	5	$^{5}_{1}6$	5	$^{4}5_{1}$	5
19	$^{1}1$	2		2	2_{2}	2		1	$^{5}7_{1}$	1	$^{4}_{1}5$	6	$^{4}7_{3}$	9	$^{5}_{2}8$	9	$^{2}_{1}5_{2}$	7	$^{9}_{1}11_{1}$	15	$^{4}_{2}8_{2}$	6
20	$^{1}1$	1	$^{5}5$	3	$^{3}_{1}5_{1}$		$^{1}3_{2}$	3	$^{3}_{1}6_{2}$	5	$^{2}_{2}5_{1}$	6	$^{6}_{2}11_{3}$	6	$^{4}5_{1}$	11	$^{3}_{3}6$	5	$^{3}_{3}8_{2}$	16	$^{3}_{1}8_{4}$	11
21	$^{1}1$	1	$^{2}_{1}3$	3	$^{2}2$	5	$^{1}2_{1}$	4	$^{4}_{1}6_{1}$	6	$^{1}2^{1}$	3	$^{6}_{1}9_{2}$	11	$^{4}_{2}8_{2}$	9	$^{2}_{2}6_{2}$	5	$^{2}_{1}3$	2		1
22			$^{3}3$	3	$^{1}1$	5	$^{2}2$	1	$^{1}_{1}2$	4	$^{2}_{1}4_{1}$	4	$^{1}_{1}4_{2}$	3	$_{2}4_{2}$	8	$^{3}_{2}8_{3}$	3	$^{5}_{1}7_{1}$	9		
23	$^{1}1$	1	1^{1}	2	$^{2}_{1}5_{2}$	1	$^{2}2$	1	1_{1}	1	$^{3}3$	2	$^{1}1$	1	$^{7}_{3}11_{1}$	7	$^{1}_{1}2$	4	$^{15}_{3}22^{1}_{3}$	17	$^{4}_{2}6$	8
24	$^{1}_{1}1$			2	$^{2}3_{1}$	1	$^{2}_{2}5_{1}$			1	1_{1}	2	$^{4}_{1}5$	4	$^{4}_{2}7_{1}$	4	$^{4}_{2}8^{1}_{1}$	7	$^{12}_{4}26^{2}_{6}$	23	$^{1}_{1}5_{3}$	11
25			$^{1}_{1}2$		$^{1}_{1}2$	1		2	$^{1}_{1}3_{1}$	4	$^{1}1$	4	$^{1}1$	1	$^{4}_{6}10_{1}$	9	$^{5}5$	7	$^{3}_{1}6_{2}$	12	$^{1}1$	3
26			$^{1}1$			2	$^{3}_{2}7_{2}$	3	$^{2}3_{1}$	2	$^{1}_{1}3_{1}$	2	$^{2}_{1}3$	6	$^{2}_{1}5_{2}$	4						
27			$^{2}2$	1	1_{1}	1	$^{2}2$	3	$^{1}1$	2	$^{2}2$	4	$^{3}_{1}4$	1	$^{1}1$	1						
28			$^{3}_{1}7_{3}$	5		3		2	$^{3}_{2}5$	7	$^{4}_{2}8_{2}$	2										
29			$^{5}_{3}13^{2}_{3}$	17	$^{2}_{1}4_{1}$	5	1_{1}	1	$^{1}_{1}2$	1	$^{1}1$	1										
30			$^{10}_{4}16_{2}$	8	$^{3}4_{1}$	13	$^{1}_{1}2$	5	$^{1}_{1}2$	1												
31				3	$^{1}_{2}3$	6	$^{3}_{2}5$	4	$^{1}1$	1												
32						1	$^{2}_{1}3$	3														

*Numbers in the left-hand column refer to 5° longitude lines, and letters in column headings refer to 5° latitude lines, as shown in Fig. 1. (Example: B-20 = 70° N, 85° W.) Figures in body of table indicate the number of times a high-pressure cell has been centered at each intersection as related to the number of times rain or no rain has occurred 30 days later. The chart summarizes daily occurrences for the months of April, May, June, July, and August, 1950, 1951, and 1952.

Values indicated in small numbers in "Rain" columns should be interpreted as follows:

light ┌──┐ very heavy

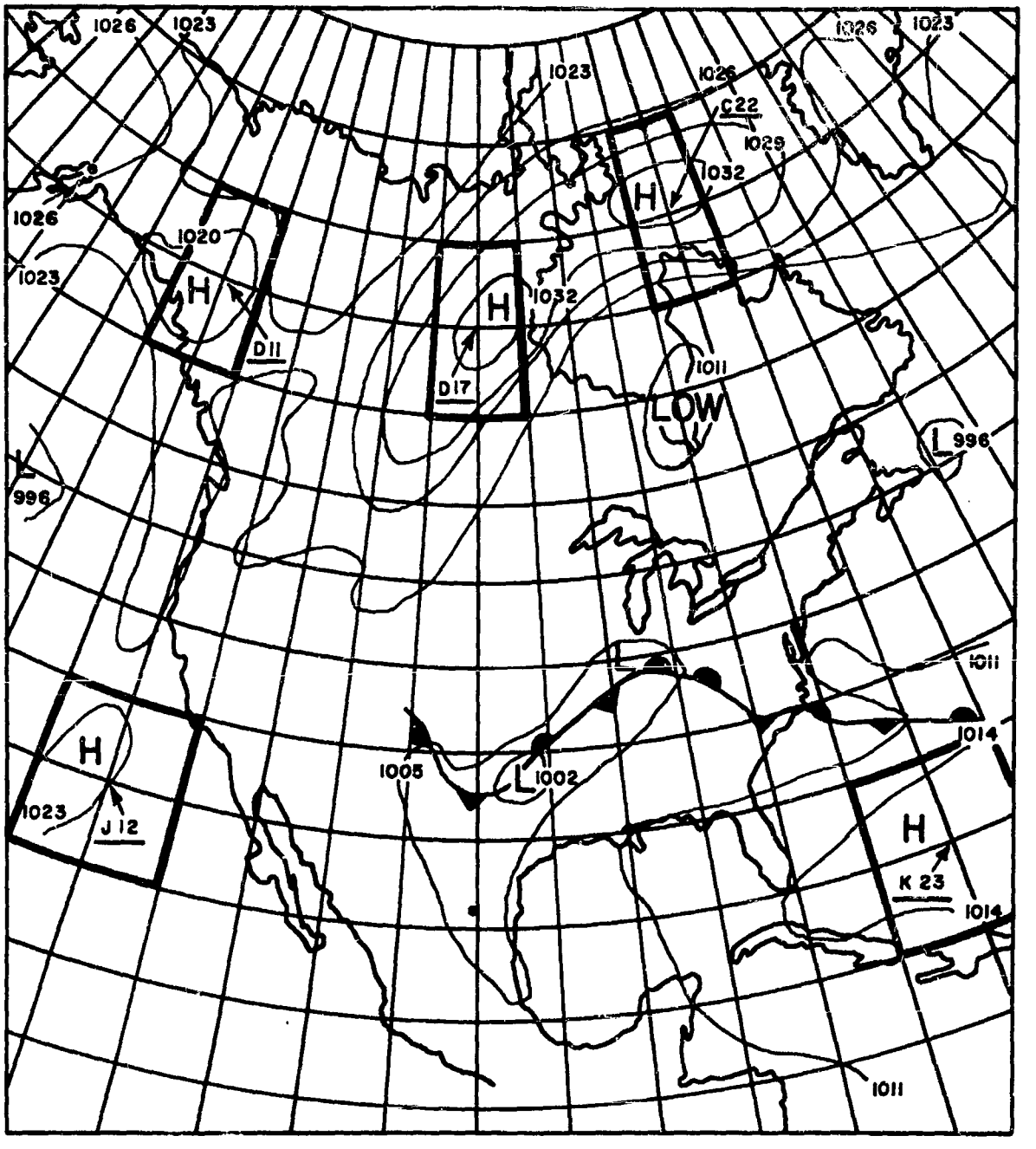


Fig. 2 Location of high-pressure centers by grid system on 1:30 p. m. surface map for May 9, 1952, as printed on Daily Weather Map for May 10. Several isobar lines have been omitted for sake of clarity.

Table III is actually a computation of a forecast for June 8, 1952, using pressure-center locations on May 9 (see Fig. 2). It can be seen that all the pressure-center locations, which were at C22, D11, D17, J12, and K23 on May 9, had more no-rain than rain occurrences, so that all the numbers, being negative, add up to a forecast for no rain at Albany on June 8. No rain was recorded in Albany during the 24-hour period from 1:30 a.m. on June 8 to 1:30 a.m. on June 9, making the forecast correct.

Table IV shows a similar computation of a forecast for rain. On April 25, 1952, pressure centers were located at C19, G19, H25, and I17. The algebraic sum of the values for each of these grid intersections as obtained from Table II reveals that there were more times when it rained than when it did not rain, so a forecast for rain is called for. Further, the sum of the total number of heavy rains is 7 compared with a total of 11 light rains. Since 7 is more than one-half of 11, the amount of rain to be expected on May 25 falls in the heavy class of 0.30 to 1.50 inches Records show that Albany received 0.68 inch, thus making this a good forecast.

Ultimately, the master forecast chart might be eliminated in favor of a master forecast grid, as shown in Fig. 3. This is simply a transparent overlay similar to Fig. 1 but with the excess of rain or no-rain cases entered directly on the grid intersections. If a larger map is used, the breakdown of light, moderate, or heavy rain could also be included at the places where there is an excess of rainy days. With such a grid overlay, the values for each pressure-center location can be read directly without reference to another chart.

The 30-day forecast for temperature departures from normal is worked up in the same way as the rain forecast. We simply find how many times over a large number of days the temperature has been much above or much below normal, above or below normal, or normal, 30 days after a high-pressure cell has been located at each of the grid intersections. Departures from normal temperature are taken from the monthly Local Climatological Data for Albany and are considered in the above-normal or below-normal classes if the departures are from 1 to 3 degrees from normal. If the departure from normal is more than 3 degrees, the much-above-normal or much-below-normal classification is used.

Table V shows the computation of a temperature forecast for June 12, 1953. The pressure-center locations on May 13 are used. The values for the number of times the temperature, 30 days later, has been in each of the five departure-from-normal classes is determined from a master forecast chart similar to Table II. Since the sum of the much-below-normal column is greater than any of the other four columns,

TABLE III

Computation of 30-Day Precipitation Forecast

	Pressure-Center Locations from Grid	Excess of Rain or No-Rain Cases Obtained from Table II	Breakdown of Number of Rain Occurrences			
			Light Tr. to 0.10 in.	Moderate 0.10 to 0.30 in.	Heavy 0.30 to 1.50 in.	Very Heavy >1.50 in.
From 1:30 p.m. Map, May 9, 1952	C22	-4	1			
	D11	-2				
	D17	-5	2	3	1	
	J12	-2			1	
	K23	-2	4	2		
		-15	-	-	-	

Forecast: No rain on June 8.

TABLE IV

Computation of 30-Day Precipitation Forecast

	Pressure-Center Locations from Grid	Excess of Rain or No-Rain Cases Obtained from Table II	Breakdown of Number of Rain Occurrences			
			Light Tr. to 0.10 in.	Moderate 0.10 to 0.30 in.	Heavy 0.30 to 1.50 in.	Very Heavy >1.50 in.
From 1:30 p.m. Map, April 25, 1952	C19	0			2	
	G19	-2	4		3	
	H25	+1	4	5	1	
	I17	+3	3		1	
		+2	11	5	(7)	

Forecast: Heavy rain on May 25.

TABLE V

Computation of 30-Day Temperature Forecast

	Pressure Center Locations from Grid	Number of Occurrences of Temperature Departure from Normal				
		Much above Normal, > +3°	Above Normal, +1° to +3°	Normal	Below Normal, -1° to -3°	Much below Normal, > -3°
From 1:30 p.m. Map for May 13, 1953	G18	8	3		1	6
	B22	1			1	2
	B23			1	1	
	J23	10	3	3	5	10
	B29	4	4	1	4	8
		23	10	5	12	(26)

Forecast: Much below normal temperature on June 12.

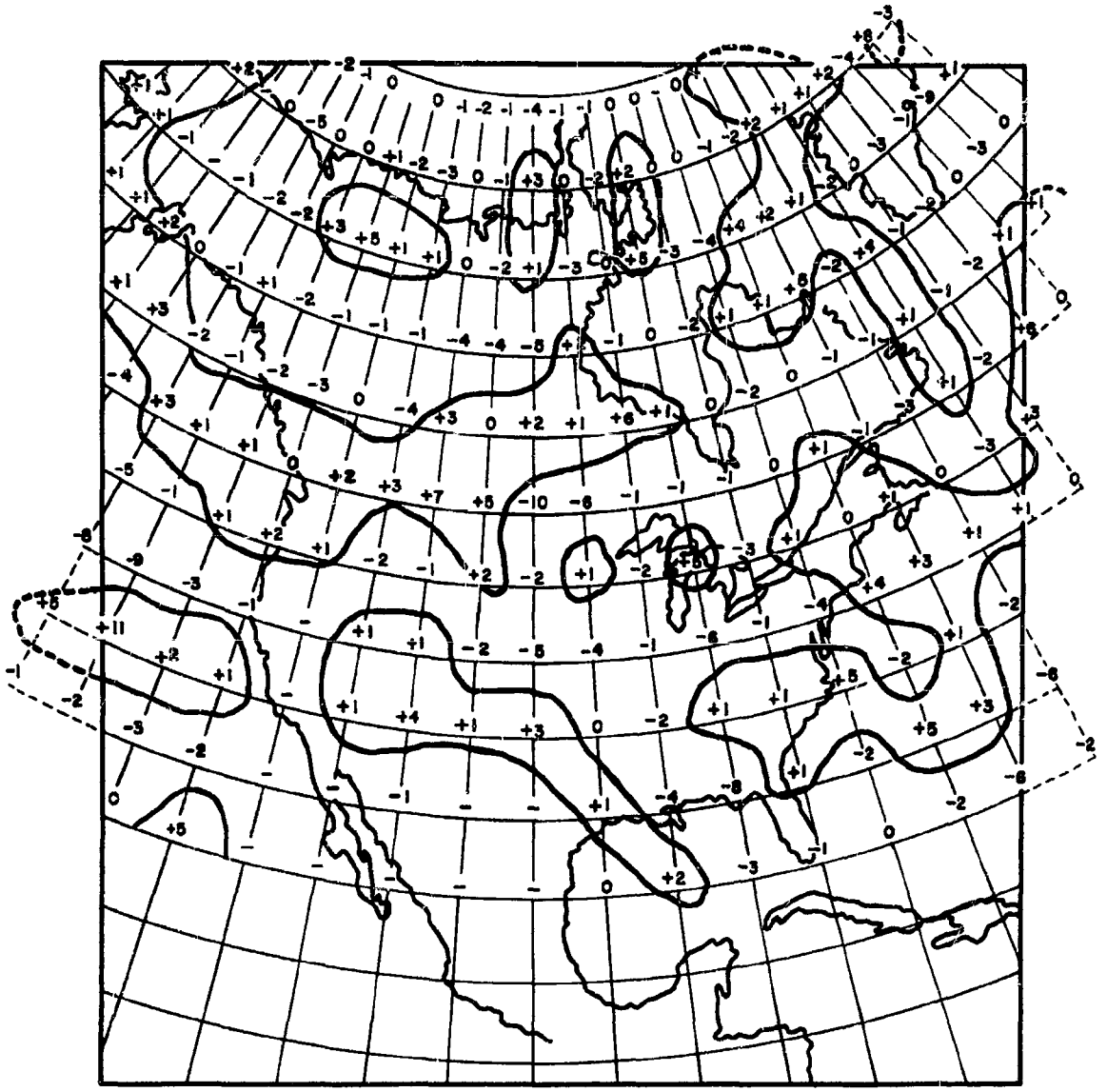


Fig. 3 Excess of rain cases (positive numbers) or no-rain cases (negative numbers) for each intersection of 5° latitude and longitude lines based on 459 days--April through August, 1950, 1951, and 1952.

a forecast for much-below-normal temperature is called for. The mean temperature at Albany for June 12 was 7 degrees below normal, making this a correct forecast.

The temperature forecasts obtained by this method have not been as accurate as we would like them to be. However, because of lack of time and personnel, only 10 months of hurriedly assembled data have been used. The temperature forecast for June 1953 was quite good, but July and August were not so good. Accuracy should improve as more years of data are incorporated in the master forecast chart. Also, we should probably consider the ratio between the total number of occurrences of temperature departures in each of the five classes during the period included in the master forecast table and apply these ratios, instead of simply adding the totals in each column and forecasting in the class that has the highest total.

Figure 4 shows our 30-day forecast (with verification) for June 1953, which was distributed to a small group of people in the General Electric Company in Schenectady. This forecast was sent out the first of June, with similar forecasts issued the first of succeeding months. We thought that by letting a few people see the forecast we would surely hear whether it broke down or whether there was something to it. As indicated later in Table VII, the per cent of correct forecasts for the month is 74 per cent, with a skill score of 0.49 on a rain or no-rain basis. If we consider that a trace of rain does not contradict a no-rain forecast yet does verify a rain forecast, as we understand some forecasters do, the percentage of correct forecasts is then 83 per cent.

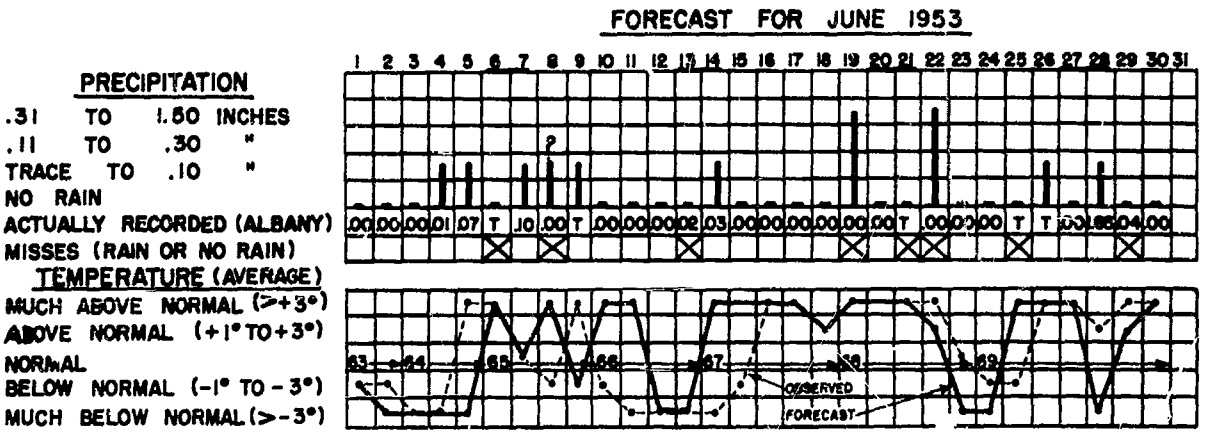


Fig. 4 Experimental 30-day weather forecast.

Occasionally, a question mark will be noted on the forecast for a given day. This indicates that the chances are only slightly in favor of the forecast indicated. This is owing to the fact that there are times when the final computation comes out with just about as many cases for rain as no rain or with one situation being favored over the other by a single case.

In verifying a forecast where a question mark is shown, we have scored it a hit if rain is called for and it actually does rain, but one-half point wrong if it does not rain. Similarly, a no-rain forecast with a question mark would be credited one-half point wrong if rain occurred on that day.

Contingency tables and skill scores based on rain or no-rain forecasts are shown in Table VI for May 1952 and for the 28-day period from June 24 to July 22, 1951. Both periods are for dependent data, and show skill scores of 0.65 and 0.68 and per cent correct forecasts of 82 per cent and 84 per cent, respectively.

From similar contingency tables, and using independent data for May 1949, June, July, August, and September 1953, we get skill scores and per cent of correct forecasts as summarized in Table VII. Highest skill seems to be in May, June, and September, with an over-all skill for the five months of 0.41. The per cent of correct forecasts for the 153 days involved is 72 per cent. In all the above, a trace of rain is considered to break a no-rain forecast. If we consider--as previously mentioned--that a trace of rain verifies a rain forecast as well as a no-rain forecast, then the per cent of correct forecasts is 77 per cent and the skill score 0.51 for the same five months.

In Table VIII, the forecast and verification for May 1949 is shown, along with results obtained when this forecast is applied to each of the months of June, July, August, and September 1953. (Only the first 30 days of each month have been used.) It may be seen that the accuracy of the forecast in the month for which it was made is much better than could be obtained using a forecast for a 30-day period picked at random. Other similar comparisons have been made and are summarized, using skill scores, in Table IX.

We have calculated by the method of variance analysis on the 25 cases in Table IX that forecasts made with this system have a significance factor of 2500. Obviously, if we allow 24 or even 12 hours on either side of a forecast day for rain, the score would be substantially improved. Several times rain occurred on a day as forecast but lasted 45 minutes or so into the next day, which called for no rain, thus causing a miss on that day.

TABLE VI

Contingency Tables Showing Results Obtained
Using the 30-Day Forecast System on Dependent Data

(Trace precipitation considered in light-rain class)

		May 1952			Mid-June to Mid-July 1951		
		System Forecast			System Forecast		
		Rain	No Rain	Total	Rain	No Rain	Total
Observed	Rain	11	4.5	15.5	12	3.5	15.5
	No Rain	1	14.5	15.5	1	11.5	12.5
	Total	12	19	31	13	15	28
		Per Cent Correct = 82 Skill Score = 0.65			Per Cent Correct = 84 Skill Score = 0.68		

TABLE VII

Per Cent Correct and Skill Scores for 30-Day Precipitation Forecast System Applied to Test Months (Independent Data)

Test Month	Per Cent Correct	Skill Score
May 1949	84	0.68
June 1953	74	0.49
July 1953	58	0.17
August 1953	66	0.19
September 1953	77	0.39
Combined (5 months)	72	0.41

TABLE VIII

30 DAY FORECAST FOR RAIN OR NO RAIN IN ALBANY-SCHENECTADY AREA FOR MAY 1949 AND COMPARISON OF ACCURACY WHEN THIS FORECAST IS APPLIED TO PRECIPITATION WHICH FELL IN OTHER MONTHS. TRACE EQUALS LIGHT RAIN ONLY.

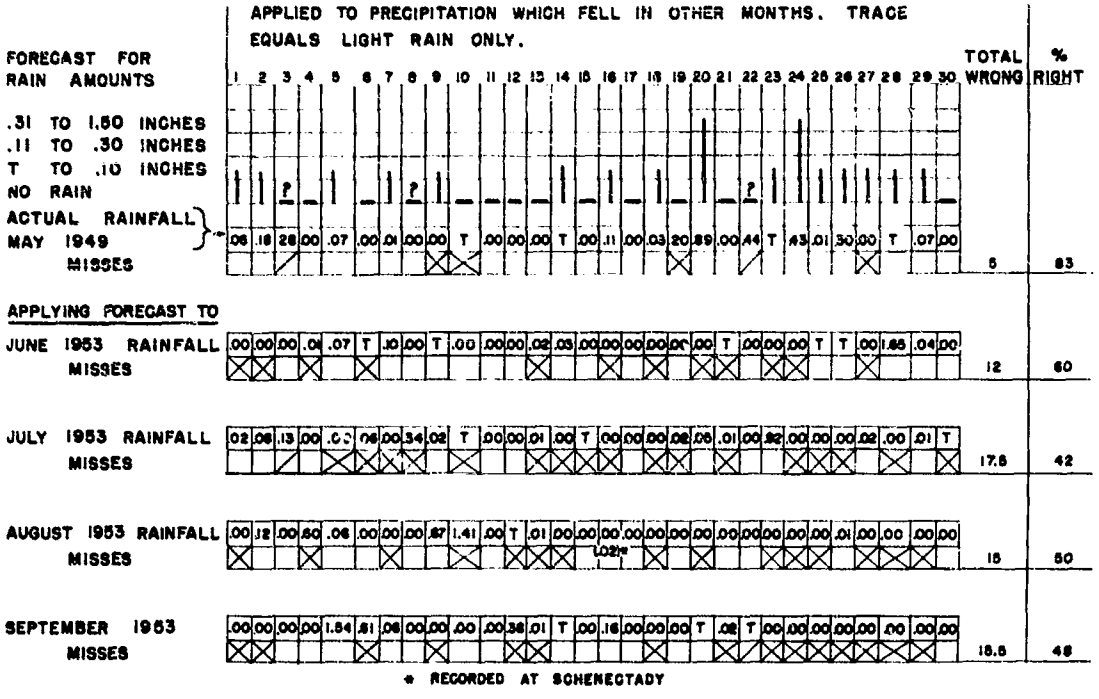


TABLE IX

Forecast Applied to Rainfall for	Skill Scores for 30-Day Rain or No-Rain Forecasts for Albany-Schenectady Area				
	May 1949	June 1953	July 1953	August 1953	September 1953
May 1949	+.68	+.15	-.05	-.01	+.09
June 1953	-.21	+.49	+.44	-.09	+.11
July 1953	.00	-.30	+.17	+.27	+.13
August 1953	.00	+.10	+.06	+.19	-.04
September 1953	.00	+.10	+.06	+.08	+.39

By variance analysis, the significance factor for months for which forecast was actually made equals 2500 (F = 16.4).

The present status of this forecast system is, of course, very crude. A rather small amount of data has been used to make up the master forecast chart and only the simplest of statistics have been tried in arriving at the forecast.

No attempt has yet been made to determine whether some sort of weighting factor is necessary. Obviously, high-pressure cells (particularly the semipermanent highs) occur much more frequently over some areas than others, yet the values in the master forecast chart are all treated alike. However, the fact that a high has occurred at some intersections only two or three times in three years (compared with 50 or more times during the same period in the semipermanent high regions) may in itself be significant.

It is expected that more data will help the system (up to a certain point), but we are not sure whether more complicated statistics will do the same. Certainly the results obtained so far would indicate that further investigation of the system is highly desirable. A master forecast chart should be made for other areas of the country to see how well the system works for other places. We have included five consecutive months--April through August--in our master forecast chart used for summer months. A similar table should be made for winter months. We expect, because of faster movement of weather systems during winter, that a master forecast chart for winter would be different from the one for summer. As a matter of fact, we may find that charts should be made for two- or three-month periods. The fact that our 1953 forecasts showed higher accuracy in May, June, and September and lower accuracy in July and August suggests this. However, it is also true that the pressure pattern of the surface map is apt to be rather flat with no outstanding highs during June and July, thus making it more difficult to determine the exact pressure-center locations. We may also find that it helps to keep the master chart up to date by adding new data into the body of the chart each day that a forecast has been verified. In this way, any current trends in the weather might be taken care of.

The greatest weakness in this system, of course, lies in correctly determining the pressure centers, particularly when they are about equally divided between two adjacent 5° intersections. This is further complicated by the fact that we cannot always be sure that the isobars are drawn correctly, since considerable interpolation by the map plotters is often necessary, particularly over ocean and arctic areas. Some improvement may be made by setting up more rigid rules as to which highs should be used. However, once the rules are set up and understood and a forecast chart made available for an area, it should be a rather simple matter to make a reasonably good 30-day forecast.

There are several forecasting systems that use a pressure grid system for locating high- and low-pressure centers, but we have not as yet found a system that attempts to relate the combined effects of several pressure centers over a large area to subsequent rainfall or temperature over a rather small area. It would seem that such statistical information would be as useful a tool in forecasting as knowing the average movement of pressure cells or simply the frequency of occurrence of low-pressure cells at various locations, because the end result is usually to determine the probability of precipitation or temperature conditions.

The use of a pressure grid system to determine high- or low-pressure centers is not a new idea.[2, 3] The investigations of G. P. Wadsworth[4] at Massachusetts Institute of Technology, however, bear the closest resemblance to our system of any that we have come across. The MIT group found that there was a significant relation between the position of the five major semipermanent high- and low-pressure cells and the attendant precipitation--either light, moderate, or heavy--over various small areas of the United States. Apparently, no attempt was made to relate the pressure-cell positions to subsequent rainfall in the form of a forecast.

We do not understand why there should be any significant relationship between the positions of high-pressure cells over North America and subsequent precipitation and temperature patterns over a selected small area 30 days later, yet the results obtained would indicate that this may be the case. In using the combined effects of all the major high-pressure centers, we are describing something about the general circulation, but its relationship to definite types of weather 30 days hence is difficult to understand at the present time. Perhaps the results are fortuitous and over a longer period the accuracy will fall off; this remains to be seen. It is very likely that for best results we should consider all the major pressure centers in the Northern Hemisphere rather than just in North America. If arrangements can be made, we plan to investigate the use of pressure centers that have been determined from the Northern Hemisphere Historical Weather Map series.

Admittedly, this forecast system is not fully developed. The work in making up the master forecast chart is rather tedious, and the time available for this sort of work has been limited. There are a great many phases of this type of analysis that should be explored. In particular, more years of data should be tried in the master forecast chart and, as mentioned previously, pressure cells over the whole Northern Hemisphere should perhaps be considered rather than just North America. Also,

levels other than the surface should be investigated, as should forecast periods other than 30 days. (For instance, 28 days might give even better results.) It may be that better short-range forecasts can be obtained by successively applying forecasts ranging from 30 down to three or four days.

We hope that this is not another forecast system that works well for a while and then never again. At least the results so far have been very encouraging.

ACKNOWLEDGMENTS

The authors are grateful for the help received in analysis of the data from Irving Langmuir, General Electric Research Laboratory, Schenectady; Max Woodbury and Leith Holloway of the Meteorological Statistics Project at the University of Pennsylvania; and Jerome Namias, Extended Forecast Section, U. S. Weather Bureau. They are also grateful to Cmdr. Daniel F. Rex, Office of Naval Operations, and Lt. Cmdr. Charles N. Palmer, Office of Naval Research, and to Ernest Johnson and James Cassidy of the Albany Weather Bureau, for supplying climatological data and other information as required from time to time, and to Vincent Schaefer, General Electric Research Laboratory, Schenectady, for continued encouragement in this work.

REFERENCES

1. Now associated with A. D. Little, Inc., Cambridge 42, Massachusetts.

2. Bowie, E. H., and Weightman, R. H., "Types of Storms of the United States and Their Average Movements," Monthly Weather Review, Supplement No. 1, 37 pp. (1914).

3. George, J. J., "Eastern Airlines Weather Map Index and File," photostatic copy of short report received by the author June 29, 1951.

4. Wadsworth, G. P., "Position of Major Pressure Cells in Relation to Rainfall," Geophysical Research Directorate Report No. 6, Contract No. W28-099-ac-398, MIT, Div. of Industrial Cooperation, Cambridge, Mass. (1949).

Part 7

OBSERVATIONS OF THE FORMATIVE STAGES OF THE WORCESTER, MASSACHUSETTS, TORNADO

Raymond E. Falconer and Vincent J. Schaefer

On June 9, 1953, a severe tornado struck the region around Worcester, Massachusetts, causing great property damage and the loss of over 100 lives. Other tornadoes were reported the same afternoon in eastern Massachusetts, southeastern New Hampshire, and near Chatham, New York.

At 0658 EST on June 9, a 120° sky camera belonging to the Munitalp Foundation and operated by Schaefer started operating. The camera was located six miles west of the Research Laboratory. It was arranged to take one picture every minute of the daylight hours. Fortunately, it was pointed east and thus obtained a nearly complete record of the cloud developments that occurred throughout the day until 1807 EST.

The sun rose behind a thick veil of cirrus clouds and throughout the morning was partially obscured by high ice-crystal clouds of the type associated with a jet stream.(1) At the Laboratory, the radioactive point showed the typical high positive current that has been correlated with the presence of a jet stream.(2) These high positive-current readings occurred from early morning to 1030 and again after 1845. Between these times, other currents obscured the effect of the jet stream and will be described later. The WBAN isotach 500-mb map for 1000 EST shows a 60-knot jet stream over the Schenectady area. Twelve hours later, the 200-mb isotach map indicates a 60- to 80-knot stream in the same vicinity.

During the morning the surface wind was averaging about 15 mph from SSE, but at 1030 it shifted nearly 90° into the SW and increased in velocity. Accompanying this wind shift, the atmospheric electricity decreased markedly to an average of zero but with both positive and negative pulses of low amplitude, which continued until 1230 EST. The time-lapse movies showed that the cloud pattern following the wind shift became predominantly cumulus congestus, with a few light precipitation areas. A smoke source several miles away showed the air to become very unstable at this time.

At 1230, several large towering cumulo-nimbus cloud formations were noted just north of the laboratory. Their vertical growth was so rapid as to resemble the effects observed with time-lapse motion pictures of large cumulus clouds. At this time, a counter-clockwise motion was observed within the cloud mass, which at that time consisted of eight to ten separate towers. While such cyclonic motions are not rare in places where clusters of local orographic cumuli form in the western mountains, such effects are rarely observed in the East. This effect, together with the presence of dry air aloft as evidenced by the rapid shredding of the cumulus towers around the edge of the cloud mass, led us to remark that conditions were suitable for tornado formation.

During this period, the sky camera shows the development of large cumulus towers shifting to anvil tops, with indications that the tops were considerably higher than 40,000 feet. As the edge of the clouds passed close to the Laboratory, the atmospheric electricity showed a strong positive deflection for about five minutes, followed by a strong negative flow for about 45 minutes, then again reversing to a strong positive current until 1400 EST. A few large raindrops fell at the Laboratory at 1235 during the period when the solar radiation record passed through a minimum. At the sky-camera location, rain fell at 1320 for a three-minute period.

As the cloud system moved toward Massachusetts, the sky over eastern New York cleared and remained in that condition the rest of the day. The center of the cloud mass had a bearing of 107°. Petersham, where the tornado first reached the ground, has a bearing of 105°. A strip of film taken between 1455 and 1505 and showing this cloud mass is given as Fig. 1. Along the southern edge of the cloud mass, some remarkable cumulus towers appeared about 1600 with a bearing of 145° to 155°. These showed extremely rapid up-and-down motions and may have been associated with a tornado reported in the vicinity of Chatham, New York, which has a bearing of 157° from the camera site.

At about 1515 EST, the radioactive-collector record showed the field becoming negative, and from then until 1820 a strong negative field was observed. It has been reported that the tornado started near Petersham, Massachusetts, at 1520 EST, or about five minutes after the field started to go negative here in Schenectady. Because of the sensitivity of the recorder, plus a stop to prevent the recorder pen from swinging too near the edge of the chart, several of the negative peaks are cut off. The dotted lines in Fig. 2 indicate what the pen probably would have shown. Thus, during the time when the tornadoes were occurring, the radioactive collector was indicating a strong continuous negative field, which is very unusual when the sky overhead is practically clear.

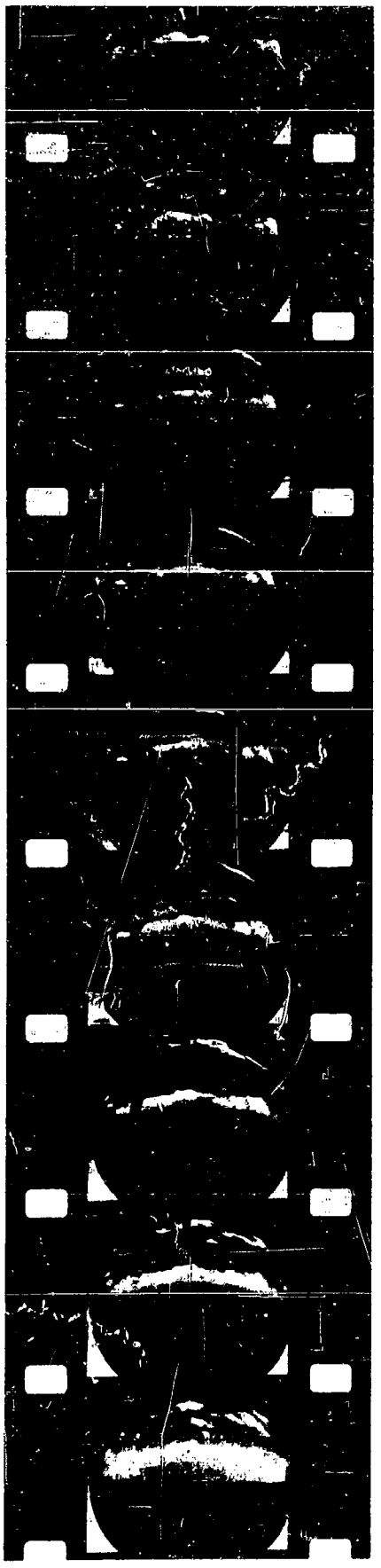


Fig. 1 Appearance of storm cloud associated with Worcester tornado between 1355 and 1405 EST, June 9, 1953.

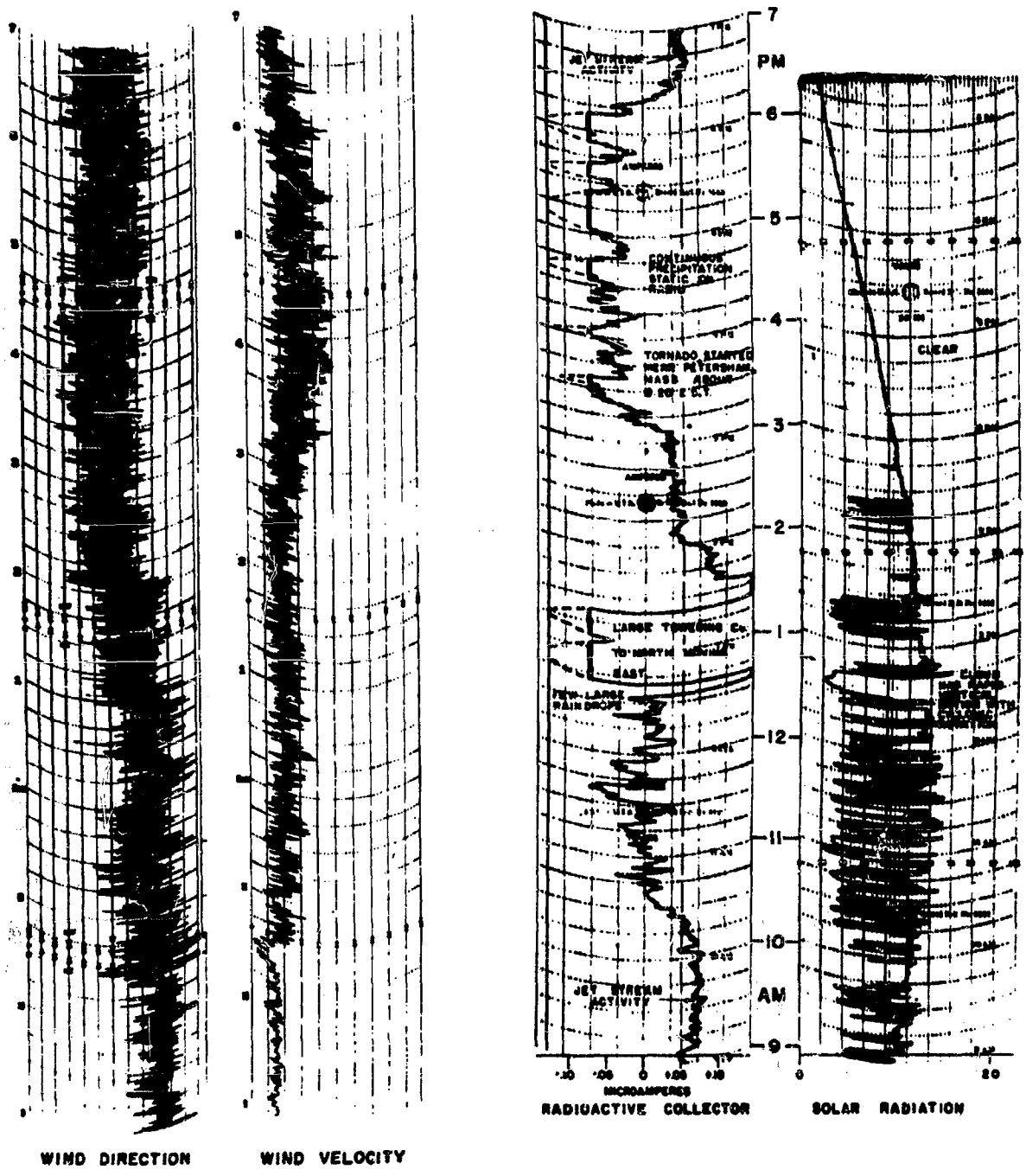


Fig. 2 Charts of wind direction and velocity, atmospheric electricity, and solar radiation related to storm that produced Worcester, Massachusetts, tornado, June 9, 1953.

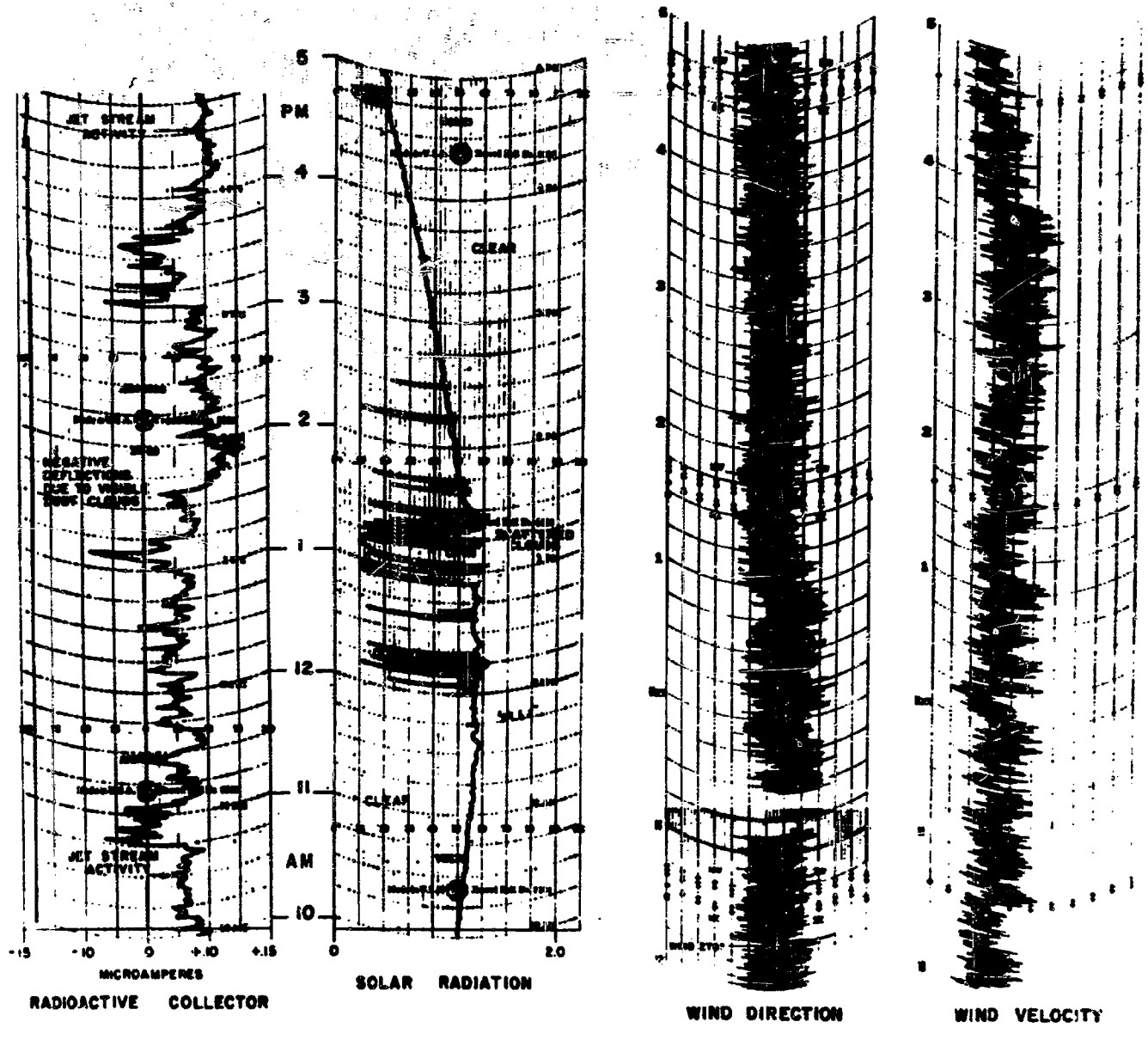


Fig. 3 Charts of atmospheric electricity, solar radiation, wind direction, and velocity associated with high winds and visible dust on April 23, 1953.

During this period, relatively strong winds occurred, averaging up to 35 mph with gusts to 53 from the west. This might have caused the flow of negative electricity. However, while some occasional negative deflections have been noted in the past during similar clear sky conditions, they have usually been associated with visible dust in the air and rarely have appeared as a continuous negative field for a period as long as that noted on June 9. As an example, Fig. 3 shows the radioactive collector trace on another generally clear day--April 23, 1953--but with scattered cumulus clouds. The wind on this day was from the west, averaging 35 to 40 mph with gusts to 64 mph, yet there is only an occasional negative deflection from an otherwise strong positive reading associated with the presence of a jet stream. By using balanced balloons, these negative deflections were definitely associated with visible dust clouds from a source about two miles west of the weather station.

During the period of strong negative field on June 9, continuous and strong precipitation static noises were heard on our long-wave receiver used to follow weather reports on the CAA radio range at Albany. This type of static apparently is common in the vicinity of tornadoes, so it is quite possible that the continuous negative field that was indicated by the radioactive collector was related to the tornado situation in Massachusetts and New Hampshire on the afternoon of June 9, 1953. Further study is required to explain the actual mechanism for this flow of electricity from a region 90 miles away.

REFERENCES

1. Schaefer, V. J., "Cloud Forms of the Jet Stream," Tellus, 5, 27 (1953).

2. Falconer, R. E., "A Correlation Between Atmospheric Electrical Activity and the Jet Stream," G-E Research Lab. Rept. No. RL-900 (July 1953).

Part 8

A POSSIBLE RELATIONSHIP BETWEEN THE SIGN OF THE POTENTIAL GRADIENT AND THE TYPE OF PARTICLES IN A CLOUD

Raymond E. Falconer

Recently, S. E. Reynolds and Howard Neil have reported[1] on laboratory experiments at the New Mexico Institute of Mining and Technology that reveal that, when a riming rod is operated in a cloud composed entirely of supercooled droplets or composed entirely of ice crystals, negligible electrical-charging effects are observed. However, when the rimer is operated in a cloud consisting of supercooled droplets and ice crystals in coexistence, a large amount of charge is separated. The sign of the charge on the rimer is positive when the crystals are numerous relative to the droplets and negative when the reverse situation exists.

It is believed that these findings may substantiate some conclusions reached by the author in 1951 regarding a possible relation between the sign and magnitude of the potential gradient and the change in state of water in clouds during stormy weather. These conclusions were based on an examination of several years of the potential-gradient records made in Schenectady, using a radioactive collector, and by the fact that other investigators[2,3] had found by laboratory experiments that a separation of charge does take place when a change in state of water occurs. The author's conclusions were as follows.

1. Positive fields are most often associated with cold temperatures. This has been noted by the author and reported in 1949.[4] Schaefer noted[5] in 1940 that what he calls "positive-current storms" (all positive field) occur mainly with dry snow at temperatures between zero and 25°F. Simpson[6] reports that light snowfall (snow at very cold temperatures is more apt to be light) usually produces all positive fields. Simpson has also noted that high positive fields in Antarctic blizzards[7] are mainly positive. Although this statement is made in relation to the Simpson-Scrase ice friction theory, it may also be closely related to the cold temperature - positive field relation. Chalmers[8] has also suggested that the sudden freezing of supercooled drops of water

Preceding Page Blank

might cause a separation of charge of the right sign and at the right temperature to account for the main separation in thunderclouds. In Fig. 1A it will be noted that an increased positive field occurred with a cold-front passage without precipitation. This is often observed mainly in winter.

Since the formation of ice crystals requires a sufficient cooling of water droplets (or water vapor), it can be seen from the above references that conditions would be most favorable for the formation of ice crystals. The predominance of a positive field under these conditions agrees in general with the Reynolds-Neil findings that a predominance of ice crystals over supercooled water droplets in a cloud produces a separation of charge such that a riming rod suspended in the cloud acquires a positive charge.

2. Negative fields in cloudy and stormy weather are most often associated with atmospheric conditions involving warmer temperatures. Again, the author has pointed this out in an earlier report.(4) Also, Simpson(6) and others have noted that the field is negative and fairly steady when there is rain due to a warm front or other stable condition. In Fig. 1C it will be noted that the field is all negative during a warm-front situation with light rain falling. Possibly related to this is the observation that the field becomes less positive with the passage of a cloud of liquid water droplets in otherwise fair weather. If drops of rain fall, the field usually goes negative.

It is believed that in some cases the effects noted in the above references may be related to the Reynolds-Neil findings that a rimer in a cloud that has more supercooled water droplets than ice crystals produces a negative charge on the rimer. In other cases, the melting of ice crystals or ice pellets as suggested by Dinger and Gunn(2) may be responsible for the negative fields observed.

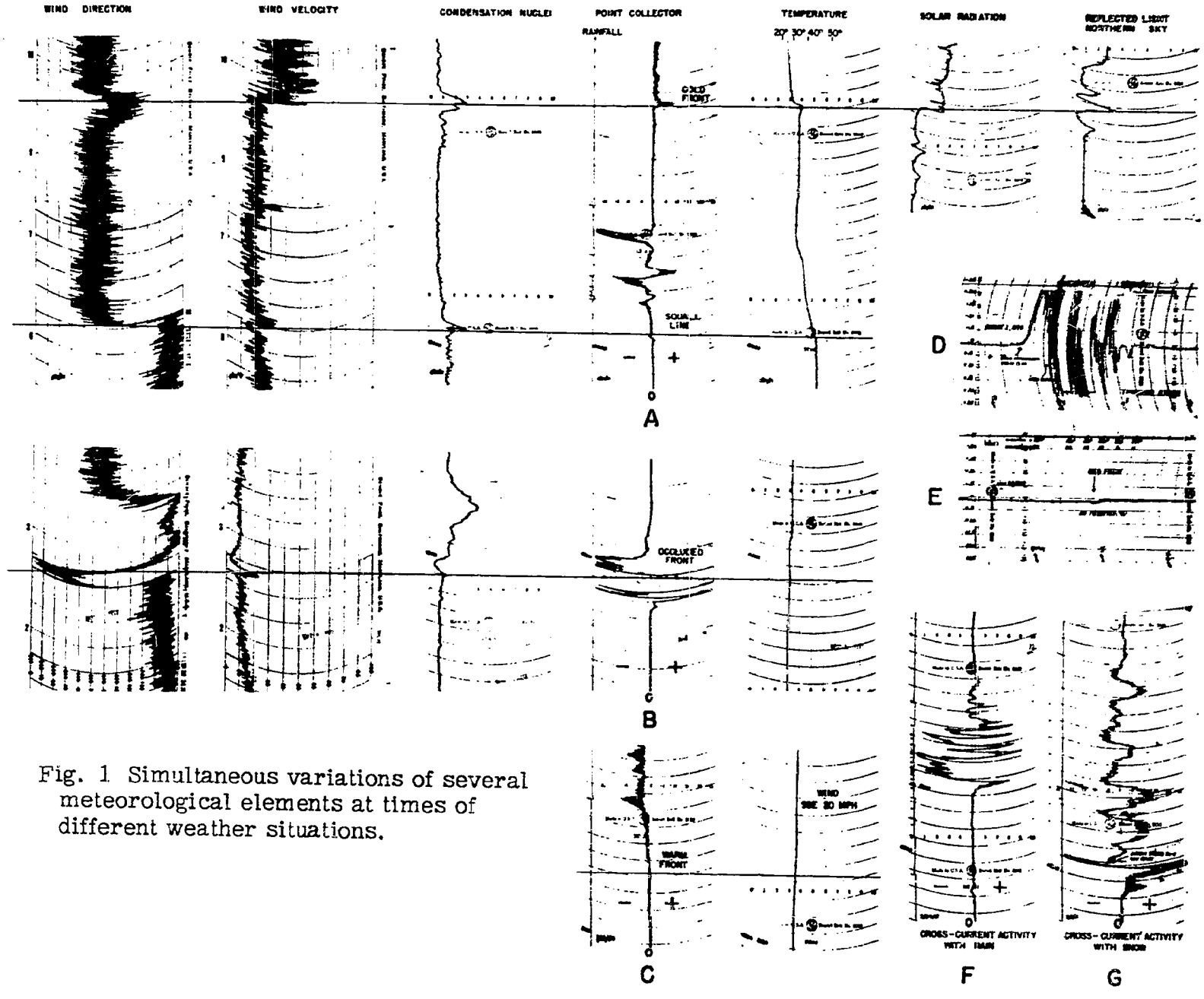


Fig. 1 Simultaneous variations of several meteorological elements at times of different weather situations.

3. Considering the previous two points, it would seem that, when we have an interaction of warm and cold air masses, conditions could and do arise in which the field alternates between positive and negative values. The field would be positive if conditions were more favorable for the growth of a large number of ice crystals and negative if conditions favored the sublimation or melting of ice crystals while the supercooled cloud droplets increased in number.

With the passage of an occluded front or a squall line (see Figs. 1A and 1B), fields of alternating sign are usually observed, particularly with precipitation falling. Such fronts involve unstable conditions, owing to the relative temperatures of the warm and cold air masses involved. Predominant ice-crystal formation in clouds associated with these fronts might be produced by warm moist air being forced to high levels by the invading colder air. While there was a predominance of growing ice crystals in the clouds, a positive field would be observed at the ground. However, because of the turbulence due to the unstable conditions involved, there would also be times when the ice-crystal supply would be diminished either by melting or because the initial supply of crystals had precipitated out and conditions were no longer favorable for new crystal formation. The balance between these two conditions is, of course, extremely variable and would depend on a number of factors.

In Figs. 1F and 1G, more regular alternations between positive and negative fields are shown, in one case for rain and in the other for snow. The rain case was February 24 and the snow case February 1, 1951. In the example of Fig. 1G, the sensitivity of the recorder was reduced by a factor of 10 after the first negative deflection of the recorder pen in order to keep the readings within the limits of the chart.

Most cross-current activity of this type occurs with temperatures near freezing or slighly above, either at the surface or at some level through which the precipitation has to fall. This is particularly true of wet snow, which produces some of the strongest fields and often rather symmetrical sine-wave patterns as the sign of the field changes. Simpson[9] has noted this but has not been able to offer any adequate explanation of the symmetrical patterns. Schaefer found[5] that "cross-current" storms were most often found at temperatures between 25° and 35°F, with wet snow falling.

It has been noted by the author that very often, during stormy weather, precipitation becomes heavier just after the field has gone positive, and continues for a time into the period of negative field. If we can assume that the Reynolds-Neil experiments bear some relation to the conclusions of the author as outlined above, this could be interpreted to mean that: (1) during the period of positive field indicated by a collector at the earth's surface, conditions were favorable for considerable ice-crystal growth, probably owing to convection of clouds to levels of sufficiently cold temperature; (2) after sufficient time these crystals grew to sizes sufficient to fall to lower levels, partially melt in the warmer air, and finally reach the ground as increased precipitation, thus temporarily depleting the supply of ice crystals and resulting in a negative field; (3) while (2) above is taking place, conditions in (1) are being repeated, and shortly the field goes positive again as sufficient numbers of new ice crystals are formed. Under some circumstances, a positive field may indicate that "overseeding" is taking place. Whether Condition (1) or Condition (2) takes place obviously depends on many factors, such as temperature distribution in the air mass, the amount of convection, the number of natural (or artificial) sublimation nuclei, etc. In extensive and long-lasting storms, conditions would probably be more favorable for symmetrical patterns in the trace of the alternating field than might be expected with frontal showers or intermittent showery conditions.

One other thought might be worth mentioning. In Part 1 of this report, a relation between higher positive-field indications during fair weather and the presence of the jet stream over the area was pointed out. In this earlier paper, the author mentioned the possibility that, in addition to the ice-friction theory, a separation of charge may take place in the formation of ice crystals at high levels which would produce a field of the right sign and magnitude to fit our observations. Undoubtedly, the ice-crystal formation process is going on almost continually in varying degrees, although cirrus clouds are not always visible. Along the axis of the jet stream there is a steep temperature gradient. It is not inconceivable that the cooling of moisture at high levels in the warmer air mass, as it mixes with the colder air mass, would result in ice-crystal formation along the axis of the jet stream. While water-droplet clouds at these levels are not always visible (a visible cloud would allow a more direct comparison with the Reynolds-Neil experiments), the reaction taking place seems to be in the right direction to produce an increased positive field due to the growth of ice crystals along the jet-stream axis. This, in combination with the ice-friction theory and the theory

previously advanced by the author that excess positive charge is acquired by the jet stream by previous passage over stormy areas, may account for higher positive fields observed in Schenectady when a jet stream is over the area.

The electrification processes that go on in stormy weather as well as in fair weather are probably not so simple as this report suggests. However, interpretation of field measurements in the light of the above suggestions should reveal some interesting information on atmospheric electricity and cloud physics, particularly during stormy weather but also during fair weather.

REFERENCES

1. (a) New Mexico Institute of Mining and Technology, "Thunderstorm Electricity," Signal Corps Research Project No. 24-172B, Final Report (1 June 1953).

   (b) New Mexico Institute of Mining and Technology, "Thunderstorm Electricity," Signal Corps Research Project 172B, Quarterly Report No. 1 (7 September 1953).

2. Dinger, J. E. and Gunn, Ross, "Electrical Effects Associated with a Change of State of Water," Terrestrial Magnetism and Electricity, 51, 477-494 (December 1946).

3. Workman, E. J. and Reynolds, S. E., "Electrical Phenomena Occurring During the Freezing of Dilute Aqueous Solutions and Their Possible Relationships to Thunderstorm Electricity," Phys. Rev., 78, No. 3 (1950).

4. Falconer, R. E., "Some Correlations Between Variations in the Atmospheric Potential Gradient at Schenectady and Certain Meteorological Phenomena," Project Cirrus Occasional Report No. 18 (1 December 1949).

5. Schaefer, V. J., "Properties of Particles of Snow and the Electrical Effects They Produce in Storms," Trans. AGU, 28, 587 (1947).

6. Simpson, G. C. in Atmospheric Electricity, by J. Alan Chalmers, p. 74 (1949).

7. Simpson, G. C. in Atmospheric Electricity, by J. Alan Chalmers, pp. 159-160 (1949).

8. Chalmers, J. Alan, Atmospheric Electricity, p. 160 (1949).

9. Simpson, G. C. in Atmospheric Electricity, by J. Alan Chalmers, pp. 74-75 (1949).

Address	No. of Copies
Chief of Naval Research, Navy Department, Washington 25, D.C. Attention: Code 416	3
Director, Naval Research Laboratory, Washington 25, D.C. Attention: Technical Information Officer, Code 2000	9
Director, Office of Naval Research Branch Office, 346 Broadway, New York 13, N.Y.	1
Director, Office of Naval Research Branch Office, 10th Floor, John Crerar Library Bldg., 86 E. Randolph St., Chicago 1, Illinois	1
Director, Office of Naval Research Branch Office, 1030 E. Green St., Pasadena 1, California	1
Director, Office of Naval Research Branch Office, 1000 Geary St., San Francisco, California	1
Director, Office of Naval Research Branch Office, 150 Causeway St., Boston, Massachusetts	1
Officer in Charge, Office of Naval Research, Navy #100, Fleet Post Office, New York, N.Y.	7
Department of Aerology, U. S. Naval Post Graduate School, Monterey, California	1
Aerology Branch, Bureau of Aeronautics (Ma-5), Navy Department, Washington 25, D.C.	1
Mechanics Division, Naval Research Laboratory, Anacostia Station, Washington 20, D.C., Attention: J.E. Dinger, Code 3820	1
Radio Division I, Code 3420, Naval Research Laboratory, Anacostia Station, Washington 20, D.C.	1
Meteorology Section, Navy Electronics Laboratory, San Diego 52, California, Attention: L.J. Anderson	1

Address	No. of Copies
Library, Naval Ordnance Laboratory, White Oak, Silver Spring 19, Maryland	1
Bureau of Ships, Navy Department, Washington 25, D.C., Attention: Code 851	1
Bureau of Ships, Navy Department, Washington 25, D.C., Attention: Code 814	1
Bureau of Ships, Navy Department, Washington 25, D.C., Attention: Code 327	2
Chief of Naval Operations, Navy Department, Washington 25, D.C., Attention: OP-533D	2
Oceanographic Division, U.S. Navy Hydrographic Office, Suitland, Maryland	1
Library, Naval Ordnance Test Station, Inyokern, China Lake, California	1
Project AROWA, U.S. Naval Air Station, Bldg. R-48, Norfolk, Virginia	1
The Chief, Armed Forces Special Weapons Project, P.O. Box 2610, Washington, D.C.	1
Office of the Chief Signal Officer, Engineering and Technical Service, Washington 25, D.C., Attention: SIGGGM	1
Meteorological Branch, Evans Signal Laboratory, Belmar, New Jersey	1
Office of the Quartermaster General, 2nd and T Sts., Washington 25, D.C., Attention: Environmental Protection Section	1
Office of the Chief, Chemical Corps, Research and Engineering Division, Research Branch, Army Chemical Center, Maryland	2
Commanding Officer, Air Force Cambridge Research Center, 230 Albany St., Cambridge, Massachusetts, Attention: ERHS-1	1

Address	No. of Copies
Headquarters, Air Weather Service, Andrews A.F. Base, Washington 20, D.C., Attention: Director Scientific Services	2
Commanding General, Air Material Command, Wright Field, Dayton Ohio, Attention: MCREEO	1
Commanding General, Air Force Cambridge Research Center, 230 Albany St., Cambridge, Massachusetts, Attention: CRHSL	1
Commanding General, Air Research and Development Command, P.O. Box 1395, Baltimore 3, Maryland, Attention: RDDG	1
Department of Meteorology, Massachusetts Institute of Technology, Cambridge, Massachusetts, Attention: H.G. Houghton	1
Department of Meteorology, University of Chicago, Chicago 37, Illinois, Attention: H.R. Byers	2
Institute for Advanced Study, Princeton, New Jersey, Attention: J. von Neumann	1
Scripps Institution of Oceanography, La Jolla, California: R. Revelle	1
General Electric Research Laboratory, Schenectady, N.Y. Attention: I. Langmuir	1
St. Louis University, 3621 Olive St., St. Louis 8, Missouri, Attention: J.B. Macelwane, S.J.	1
Department of Meteorology, University of California at Los Angeles, Los Angeles, California, Attention M. Neiburger	1
Department of Engineering, University of California at Los Angeles, Los Angeles, California Attention: L.M.K. Boelter	1
Department of Meteorology, Florida State University, Tallahassee, Florida, Attention: W.A. Baum	1

Address	No. of Copies
Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, Attention: C. Iselin	1
The Johns Hopkins University, Department of Civil Engineering, Baltimore, Maryland, Attention: R. Long	1
The Lamont Geological Observatory, Torrey Cliff, Palisades, N.Y., Attention: M. Ewing	1
The Johns Hopkins University, Department of Physics, Homewood Campus, Baltimore, Maryland, Attention: G. Plass	1
New Mexico Institute of Mining and Technology, Research and Development Division, Socorro, New Mexico, Attention: E. Workman	1
University of Chicago, Department of Meteorology, Chicago 37, Illinois, Attention: H. Riehl	1
Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, Attention: A. Woodcock	1
General Electric Research Laboratory, Schenectady, N.Y., Attention: V. Schaefer	1
Geophysical Institute, University of Alaska, College, Alaska, Attention: C.T. Elvey	1
Blue Hill Meteorological Observatory, Harvard University, Milton 86, Massachusetts, Attention: C. Brooks	1
Department of Meteorology, University of Washington, Seattle 5, Washington, Attention: P.E. Church	1
Laboratory of Climatology, Johns Hopkins University, Seabrook, New Jersey, Attention: C.W. Thornwaite	1
Institute of Geophysics, University of California at Los Angeles, Los Angeles, California Attention: J. Kaplan	1
Department of Meteorology, New York University, New York 53, N.Y., Attention: B. Haurwitz	1

Address	No. of Copies
Texas A and M, Department of Oceanography, College Station, Texas, Attention: J. Freeman, Jr.	1
Massachusetts Institute of Technology, Department of Meteorology, 77 Massachusetts Ave., Cambridge 39, Massachusetts, Attention: T.F. Malone	1
Cornell University, Department of Agronomy, Division of Meteorology, Ithaca, N.Y.	1
Pennsylvania State College, School of Mineral Industries, Department of Earth Science, State College, Pennsylvania, Attention: H. Neuberger	1
Rutgers University, College of Agriculture, Department of Meteorology, New Brunswick, New Jersey	1
University of Texas, Department of Aeronautical Engineering, Austin, Texas, Attention: K.H. Jehn	1
University of Utah, Department of Meteorology, Salt Lake City, Utah, Attention: V. Hales	1
University of Wisconsin, Department of Meteorology, Madison, Wisconsin, Attention: V. Suomi	1
National Advisory Committee of Aeronautics, 1500 New Hampshire Ave., N.W., Washington 25, D.C.	2
U.S. Weather Bureau, 24th and M. Sts., N.W., Washington 25, D.C., Attention: Scientific Services Division	2
Committee on Geophysics and Geography, Research and Development Board, Washington 25, D.C.	2
Air Coordinating Committee, Subcommittee on Aviation Meteorology, Room 2D889-A, The Pentagon, Washington, D.C.	1
American Meteorological Society, 3 Joy St., Boston 8, Massachusetts, Attention: The Executive Secretary	1

Address	No. of Copies
Research Professor of Aerological Engineering, College of Engineering, Department of Electrical Engineering, University of Florida, Gainesville, Florida	1
University of Pennsylvania, Department of Statistics, Wharton School, Philadelphia 4, Pennsylvania, Attention: Professor Max A. Woodbury	1